

Department of Industrial Development
Government of Newfoundland and Labrador

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CRUSE OUTING
1980-81



Funding for this study was jointly provided by the Federal Department of Regional Economic Expansion and the Newfoundland and Labrador Department of Industrial Development under the Planning Subsidiary Agreement of the Canada/Newfoundland General Development Agreement.

Mr. I. Palmer
January 31, 1980
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from icebreaker operations indicates that there was heavy ridging over a large part of the lake in the winter of 1966-67. In recent winters, conditions have been less severe as evidenced by ice surveys carried out in 1978 and again in 1979 as a part of the present study. The primary hinderance to navigation in the pack is pressure arising usually from onshore winds acting on ice of high concentration.

The transit model was run utilizing the specifications and performances of three vessels, the Canadian Coast Guard icebreakers, Louis St. Laurent and Franklin, and the icebreaking bulk carrier, M.V. Arctic. The model results, along with studies of winter navigation in other areas, indicate quite strongly that winter navigation into Lake Melville is generally possible with an icebreaker which can generate in the order of 20,000 hp. Less powerful icebreakers generating approximately 14,000 hp would be successful in extending the navigation season during average ice conditions. However, in thick or ridged ice in the lake or in pressure situations in the pack, the lower powered icebreakers would probably incur unacceptably long transit times.

Based on the present study, it is recommended that 1) a program be undertaken to collect environmental data in the Lake Melville, Groswater Bay region over at least five winter seasons; 2) a pilot study be undertaken to evaluate the performance of a vessel operating in ice conditions in the area and to determine the operational feasibility of extending the present navigation season and 3) a detailed economic analysis of cargo transport into Lake Melville on a year-round basis be carried out.

As per your request, fifty (50) copies of the report are submitted. The report also contains three appendices which are included under the same cover. A separate report by C-CORE covering work carried out as a part of the field program is submitted in five volumes under separate cover.

If you wish to discuss any parts of the report, please do not hesitate to contact the project manager, Mr. R.J. Gill, or the undersigned.

Yours very truly,

Wilson E. Russell

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Director,
Ocean Engineering

WER/slh



101-04952/

Department of Industrial Development
Government of Newfoundland and Labrador

LAKE MELVILLE/OFFSHORE LABRADOR
YEAR-ROUND NAVIGATION STUDY
1978 - 1979



Funding for this study was jointly provided by the Federal Department of Regional Economic Expansion and the Newfoundland and Labrador Department of Industrial Development under the Planning Subsidiary Agreement of the Canada/Newfoundland General Development Agreement.

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1. INTRODUCTION

This study was commissioned in December, 1978 by the Department of Industrial Development, Government of Newfoundland and Labrador to investigate various aspects of year-round navigation into Lake Melville, Labrador. The study, which involved field and analytical programs, was conducted by NORDCO Limited as prime contractor with sub-contract work being carried out by REMOTEC Applicatons, Inc., FENCO (Nfld.) Limited and German and Milne. Partial support was also given to C-CORE under contract for an investigation carried out during the field program. A draft report was submitted to the client in September 1979 and the present document constitutes the final report of the study.

The study is an initial attempt to investigate the feasibility of year-round navigation into Lake Melville by commercial vessels. At present, traffic operates to and from Goose Bay in general from mid-June to late November and is primarily concerned with the transportation of freight and passengers. The pack ice off the Labrador Coast and the ice cover on Lake Melville prohibit ship movement from December to June. These conditions and the expected performances of ships navigating in them constitute the main aspects of the present study.

The purpose of the field program portion of the study was to enhance the amount of information available on Lake Melville during the winter season and in particular to determine the characteristics of areas which might pose special problems to winter navigation. It was believed that the major problem in the lake itself would be the occurrence

of severe ridging at the eastern end resulting in an ice jam. The pack ice characteristics pose many problems to navigation, the most important of which are high concentration and consolidation, pressure ridging, and multi-year floes. The field data collection was carried out in January, 1979 and April, 1979 with the main emphasis placed on studying conditions in the lake. The findings of these field programs are documented in Appendix C of this report.

While the successful navigation of the pack ice is an academic question given a sufficiently large and powerful icebreaker, the aim in the analytical portion of this study was to document the environmental conditions which might affect the navigational capability of a ship operating year-round in the study area and to determine the performance and general characteristics of a vessel which could operate effectively under these environmental conditions.

A significant amount of the information collected on the environment of the Labrador Sea (especially ice information) is of a proprietary nature and was not available to this study. Such information could enhance our knowledge of ice features and winter conditions in the Labrador Sea in general and would probably provide a better understanding of the occurrence and characteristics of multi-year ice, ridges and other features of the Labrador pack. The description of environmental conditions, as outlined in this report and as they constitute hazards to navigation, has been derived from published information, remotely sensed imagery and NORDCO's in-house research programs.

In order to determine the performance of a vessel under various environmental conditions, a computer model based on ice resistance and icebreaking theory was developed and from this model, the transit times of vessels were determined at various times of the year from freeze-up to breakup. It was considered instructive to select existing Canadian vessels and test their capability in coping with the ice conditions in the study area, and the appropriate parameters of these ships were used in the computer model to generate transit time outputs. It is noted here that no consideration has been given to Canadian Government regulations with regard to icebreaker support for any future year-round activity in the area, and the selection of the icebreakers for use in the computer model is not meant to presume that such will be made available in the event that a year-round operation is undertaken. A preliminary study of suitable icebreaking cargo ships for the area was carried out by German and Milne, and the results of that investigation are reported in Appendix B.

The ice conditions used in the computer model were obtained from the Atmospheric Environment Service (AES) Ice Central ice charts. Twice weekly charts for the years 1969-79 were used to determine transit times for each week from freeze-up to breakup over this period. The ice conditions were coded and digitized and were fed into the computer model along with other environmental factors which would affect ship speed. The ice conditions as portrayed on the ice charts are determined from overflights, satellite imagery and weather forecasts.

While an analysis of the factors affecting navigation in the study area and a subsequent determination of ship performance and capability were essential to the study, it was felt that the experience which has been gained in navigating in ice in general, and in the study area in particular, was of considerable importance. Accordingly, a review of experiences in other areas was undertaken in order to determine whether precedents have been set and how such experiences relate to the study area. Thus, particular attention was given to the Gulf of Bothnia in which ships operate year-round. Where possible, experiences in the Soviet Union, the Canadian Arctic, Gulf of St. Lawrence and Alaska were also investigated. Studies on extending the navigation season in the Great Lakes were also reviewed, and while these are mainly concerned with ice management techniques (as opposed to icebreaking and navigating) in freshwater ice, they do have some relevance for the study area.

In order to document navigational experiences in the study area, NORDCO retained the services of Captain E.F. Anthony of St. John's who has had several years experience operating ships in the area as well as the Canadian high Arctic. In addition to relating his own experiences in ice navigation, Captain Anthony reviewed the logs of various shipping companies who have operated in the study area. These experiences are summarized in Section 5 of this report.

The study area is shown in Figure 1.1. It is considered to cover Lake Melville and Groswater Bay and the offshore region to 52°W longitude

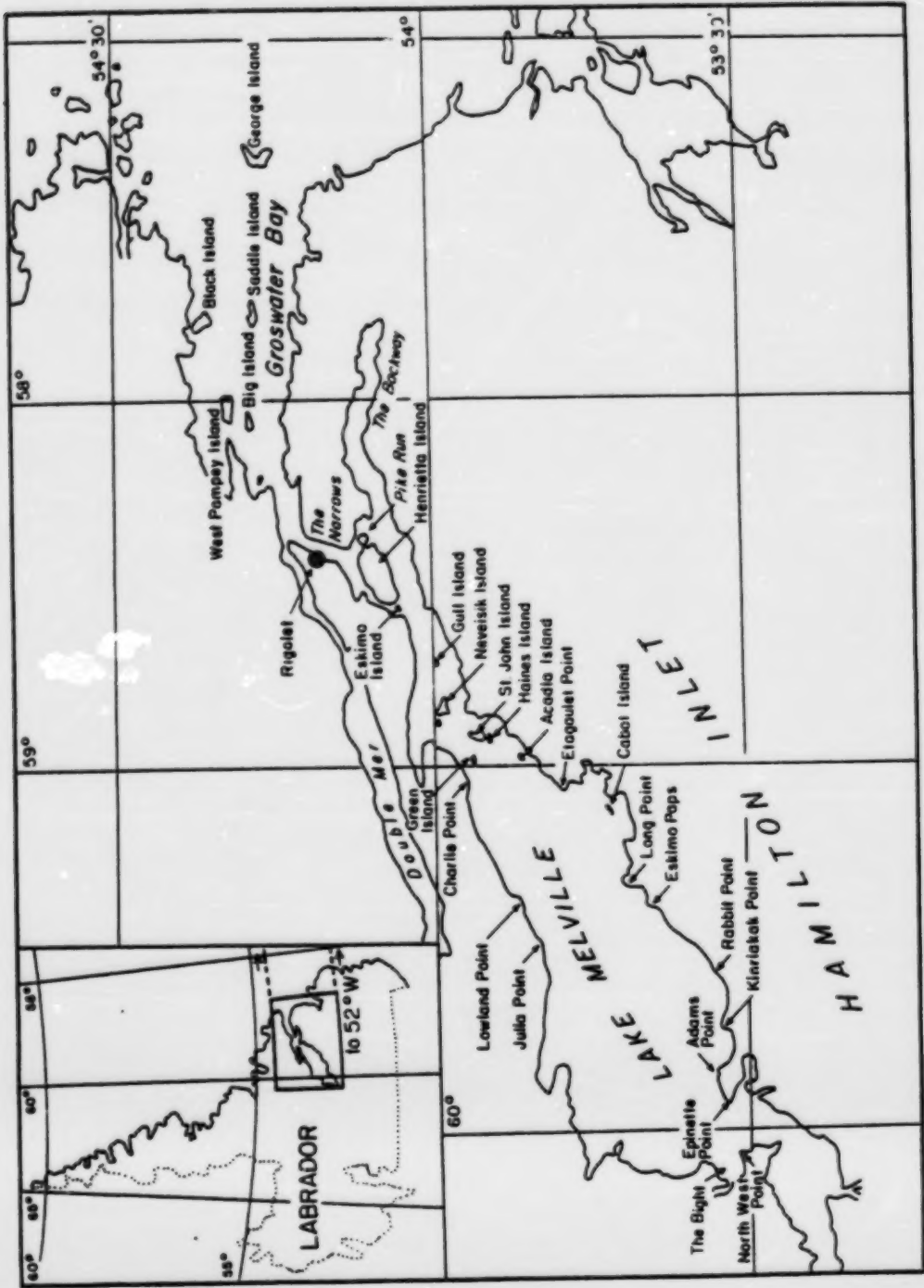


FIGURE I.1 STUDY AREA

which allows for the maximum extent of the ice edge. While data from outside this area will obviously be used as well in some cases to document ice and iceberg conditions and behaviour and to determine storm patterns, for example, the study area will be restricted primarily to the specified region. While Goose Bay is very attractive as a year-round port because of its considerable infrastructure, it is not considered to be a part of the study area because of its low bathymetry and small area which would create problems for manneuvering large ships during winter conditions; however, Goose Bay data are used when appropriate to determine ice conditions on the lake.

2. PREVIOUS STUDIES

2.1 General Transportation Studies

Probably the most comprehensive study to date has been carried out by Bradford (1973) for the Department of Transport of the Canadian Government. The study discussed the environmental factors affecting the existing navigation season in the Newfoundland-Labrador area in general and the performance of existing ships during the navigation season. Among other factors, the study considered the problem of delays due to ships being beset in pack ice and attempted to relate susceptibility to being beset to ship parameters, specifically the horsepower to foot length (hp/fl) ratio. The study was essentially limited to the existing, relatively low-powered passenger and cargo ships but did attempt an extrapolation to operation in heavier ice conditions in an extended navigation season.

The author used ice conditions for the period 1961 to 1972 and ranked these conditions on a scale from 1 to 30 based on the concentration and thickness of the ice, a larger rank implying a greater impediment to navigation. Rank 30 is considered to be equivalent to 10/10 coverage of first-year ice consisting of large floes over 30 cm thick. Based on the ability of existing ships in certain ice conditions, it is suggested that a ship with a horsepower-to-length ratio of 50 would be the minimum required to navigate in such conditions.

The author explores the feasibility of extending the navigation season into Goose Bay and suggests that a vessel of approximately 21

hp/fl in conjunction with an icebreaker could operate in Lake Melville during mid to late December. It is assumed that the ice conditions would correspond to rank 11 which would be essentially 7-9 tenths ice coverage of about 30 cm thickness. Based on the twelve years of ice data used in the study, it is concluded that the approaches to Goose Bay would be blocked for nine years out of twelve by December 18 for a 21 hp/fl vessel. However, as is discussed in the present study, navigation into Lake Melville shortly after freeze-up is largely dependent on ice conditions at the eastern end of the lake, and while conditions in the major part of the lake may be surmountable by a ship with 21 hp/fl, this may not be the case at the eastern end.

A study carried out by Stevenson Hardtke Resources (1968) for Melville Forest Products Limited dealt with the use of Goose Bay as a loading terminal for wood chips to be used at the Labrador Linerboard Mill in Stephenville. Navigation in Lake Melville and the offshore is only briefly mentioned as the study is primarily concerned with port facilities in Goose Bay. The navigation season is assumed to be five-six months long and the principal vessel is assumed to be a bulk carrier with 77,000 DWT displacement. It is stated that the draft of this vessel would be in the order of 10 m and would experience difficulty (mainly due to its beam) in the Goose Bay Narrows which would be dredged in order to accommodate the vessel. During the actual operation, the largest carrier used had a 32,000 DWT displacement (Report by Royal Commission on Labrador, Vol. IV).

Culshaw (1977) discussed marine transportation in offshore Labrador in a general manner and made reference to the effect of the ice environment on shipping in the area. The author concluded that seasonal shipping would probably be continued for some time as the relatively small market and the relative ease of stockpiling preclude the extra expense associated with year-round shipping.

2.2 Ice Studies

2.2.1 Lake Melville

The most comprehensive studies carried out on the ice conditions of Lake Melville were conducted by Memorial University of Newfoundland during the winters of 1972-73 and 1973-74 (MUN 1973, 1974). During these studies, ice thickness surveys were carried out over the entire length of the lake and covered the period from freeze-up to breakup. In addition to direct on-ice testing, data were collected by aerial reconnaissance and icebreaker probes, and oceanographic and meteorological conditions were also monitored. A preliminary study was carried out during the winter of 1971-72 during which information was gathered on ice characteristics and two icebreaker probes were undertaken with the co-operation of the Ministry of Transport of the Canadian Federal Government.

As it happened, freeze-up during the winter of 1972-73 produced very severe ice conditions in the eastern end of the lake which were apparently unprecedented. A storm which occurred in early December with winds from the west at 105 km/hr caused the ice to bear down on the

narrow section at the east end of the lake and produce extensive rafting and ridging in the vicinity of St. John and Green Islands. Thicknesses of 1.5 to 2.0 m of rafted ice were common throughout the entire eastern half of the lake and ridge depths in the order of 5 m were measured while in a few places depths of 10 m were estimated. The ridges were often several kilometers long with the most significant ridge measuring at least 3 km wide by 10 km long just to the west of St. John Island. Examinations of internal ridge structure revealed that the sail portions had porosities of 40-50 percent while the keels were estimated to have porosities of 20-30 percent. The keels were composed of hard ice underlain by softer ice which provided little resistance to drilling. Further considerations of freeze-up during 1972 are contained in Section 3.3 of this report.

This program was continued during the 1973-74 season, and although ice conditions were more moderate compared with the previous winter, significant ridging was evident in the Green Island area with the largest ridge being near the location of the largest ridge measured during 1972-73. This ridge, which extended from Charley Point to just south of Green Island, was observed with a side-scan sonar in March, 1974 and it was determined that the underwater portion extended to approximately 12.8 m below the surface. While this is clearly a significant formation, it is important to realize that conditions on Lake Melville during the 1973-74 season were in general moderate and were felt not to be of a magnitude to prove unmanageable from a navigation point of view.

In a brief survey carried out for the Department of Industrial Development of the Government of Newfoundland and Labrador in April 1978, ICE Engineering Limited conducted overflights and made ice thickness measurements at nine locations on Lake Melville running from Terrington Basin to Eskimo Island. In general, the ice cover was relatively undisturbed and no significant formations were reported in the eastern end of the lake as evidenced in previous surveys. Ice thicknesses near Eskimo, Green and St. John Islands were approximately 1 m, and the only significant formation occurred as hummocked ice between Etagaulet and Rabbit Points with the formation extending to the center of the lake off Long Point. Ice thicknesses in this field taken at three locations averaged 3.8 m and the porosity was approximately 20 percent. The individual plates comprising the field had thicknesses of 0.2 to 0.3 m thus indicating that the formation had been created early in the season.

2.2.2 Groswater Bay

There is little documented information available on surveys of ice conditions in Groswater Bay. Two overflights which were conducted during the studies referred to in Section 2.2.1 in 1972/73 resulted in limited information on ice conditions late in the season, and NORDCO carried out some further observations during 1977. In the latter study a total of six overflights of Groswater Bay was made from January to March, 1977. Ice conditions in the bay during this time were light, and ground truthing was attempted only twice during the survey period. Ice thickness measurements made in landfast ice ranged from 0.24 m to 0.28 m.

Open water existed throughout the survey from Eskimo Island to Rigolet with Pike Run being covered to varying degrees with ice pans and slush in late February and early March but was ice free during the last overflight on March 8, 1977. The north shore of Groswater Bay was ice free for the total survey period.

During an overflight on May 24, 1974, Memorial University personnel photographed ice conditions on Lake Melville and Groswater Bay and a portion of the landfast and pack ice from Cape Makkovik to Cartwright. At this time, the northern half of Groswater Bay was completely open with scattered small loose ice and a few small bergy bits. The southern half of the bay was completely ice covered; however, cracks and leads were visible in all directions in what appeared to be landfast ice.

A flight made on April 22, 1978 by ICE Engineering Limited revealed that the ice edge in Groswater Bay was encountered 50 km east of Rigolet, and this cover extended west for 20 km. Beyond this point one-tenth ice coverage existed as far west as Eskimo Island on the western side of Henrietta Island and as far as The Backway on the eastern side. Open water existed at Rigolet.

2.2.3 Offshore Labrador

While a considerable amount of knowledge exists on conditions in the Labrador Sea which would affect year-round navigation into Lake Melville, the bulk of the documented work has been carried out by oil companies engaged in exploratory drilling and is not yet available in

the public domain. In addition, the experiences gained by mariners in the area over many decades have, for the most part, not been documented in previous studies; however, in this work, an attempt is made to use such knowledge, and this is related in a later section of this report.

Most of the published information on conditions in the Labrador Sea is based on in-situ studies conducted during ice-free conditions or on data gathered remotely. The only available studies related to field programs during winter are those conducted by Amoco staff in March, 1971 and NORDCO personnel in February 1977. The former study was carried out from a sealing vessel in March and reported measurements of ice thickness and mechanical properties as well as general ice and meteorological conditions. The NORDCO research program was concerned with the documentation of a number of features of the pack ice as well as the behaviour of a ship in the pack. The ship was placed in heavy ice off Saglek and drifted south while various programs were carried out. Further references to these studies are made in the following sections of this report.

2.3 Icebreaker Probes Into Lake Melville

While Canadian Coast Guard icebreakers assist navigation in the pack ice off Labrador and in Lake Melville when necessary, there has been little documentation of the performance of the vessels under various ice conditions. The most comprehensive reporting of icebreaker performance on Lake Melville has been carried out by Memorial University of Newfoundland personnel during the cruise of the JOHN A. MACDONALD in May, 1973

(MUN, 1974) and Bradford (1979) during probes by the MACDONALD and LOUIS ST. LAURENT in 1972. The former report is essentially a qualitative treatment of the icebreaker performance and behavior while the latter relates the performance to power output and ship speed. In addition to those reports, limited documentation exists on the performance of icebreakers operating in the area during normal icebreaking missions. The experiences of these operations are summarized in the following paragraphs.

2.3.1 February, 1965

The only known attempt to negotiate Lake Melville in the middle of winter occurred during a probe of the CCGS JOHN A. MACDONALD from February 17 to 22, 1965 (Bradford, 1979). The ship travelled to Groswater Bay via the Strait of Belle Isle and reached as far as Haines Island in eastern Lake Melville. The maximum ice thickness reported both in the pack and the lake was 1.1 m (42 inches).

2.3.2 May, 1965

In late May, 1965 the D'IBERVILLE successfully travelled across Lake Melville as far as Epinette Point in the western end of the lake. Ice thicknesses in the lake were reported as ranging from 0.6 m (24 inches) to 1.2 m (48 inches).

2.3.3 January, 1967

The D'IBERVILLE was again dispatched in mid-January, 1967 to investigate the possibility of reaching Goose Bay. The ship reached the

east end of Lake Melville without difficulty, but the ice conditions further west were beyond the capability of the vessel and the project was terminated. No ice thicknesses are reported, but barring any major formations blocking the path of the vessel in the eastern end of the lake, it is somewhat surprising in light of the ship's performance during 1965 that she did not progress beyond the eastern end. General ice thicknesses during January would be considerably less than in May although the ice would be weaker during the late season.

2.3.4 May, 1967 Probe

During this probe by the MACDONALD which occurred during the first week in May, (Van Humbeck, 1967) fast ice was not encountered until the ship reached Eskimo Island, Groswater Bay being essentially open water. From Eskimo Island, the MACDONALD steamed towards the south of Haines Island and averaged a speed of 2 knots while ramming frequently in ice 1 to 1.5 m in thickness. A large area of very rough ice was experienced from Haines Island to a position off Kinriakak Point (Figure 1.1). The ice was heavily ridged and the vessel was required to ram continuously which resulted in a gain of less than 2 km per hour. Ice thickness measurements were limited to a depth of 3 m, and as a result some ridges were not drilled completely through. Off Adams Point (Figure 1.1), the MACDONALD worked for 3 hours in a ridge before breaking through. The length and width of this ridge are not reported; however, it is noted that the ice was covered with snow and showed little sign of deterioration.

2.3.5 December, 1968 - January, 1969

In late December 1968, an attempt was made to escort into Goose Bay a cargo vessel loaded with machinery for the Churchill Falls hydro-electric project. The JOHN CABOT was the first ship assigned to that mission but developed engine trouble and was joined by the LABRADOR. The attempt to reach Goose Bay was not successful because of heavy ice conditions near the Goose Bay Narrows and the ship left the area about January 6, 1969.

2.3.6 January, 1972

The JOHN A. MACDONALD conducted a five-day trial in Lake Melville in early January, 1972 and a detailed report on that probe has been prepared by Bradford (1979). The author reports that no attempt was made to enter Goose Bay for fear of sustaining damage while breaking through the Goose Bay Narrows. The vessel did however travel to within 2 miles of North West River.

Two problem areas encountered on the inbound transit were eastern Lake Melville between St. John Island and Lowland Point and along the Labrador coast in the vicinity of 53°N latitude. In both areas, the ship was required to resort to the ramming mode of icebreaking and the average forward speed was reduced to less than a knot. On the outbound transit, the ship traversed the track on the lake created during the inbound voyage and operated in the continuous mode for the entire length of the lake. In the pack, the continuous mode was interrupted only once for a brief period in first-year ice under pressure in the Strait of Belle Isle. The elapsed time for the inbound transit from the

Strait of Belle Isle to North West River was 100 hours as compared with 25 hours outbound.

Measurements of the thickness of upturned ice pieces were taken at random intervals along the track in the lake and at eighteen selected sites by auger. Thicknesses ranged from 0.36 m to 0.91 m. The general pattern indicated relatively light ice at both extremities of the lake and heavier ice in the open lake especially in the eastern half where considerable ridging was evident. A spot measurement of 0.53 m in Goose Bay indicated that ice conditions there were near normal for the time of year since measurements over a six-year period indicate that 0.51 m is normal for early January.

In the lake during the inbound transit, the MACDONALD operated in a continuous mode from Eskimo Island to St. John Island and averaged six knots during that portion of the voyage. Fifteen ice thickness measurements along the track averaged 0.36 m and there was little ridging and rafting. From St. John Island to Lowland Point, rough ice was encountered, the mean thickness along the track being 0.69 m and the maximum measuring 1.17 m.

The MACDONALD had to resort to ramming for the total distance of 14 miles between Green Island and Lowland Point and required 14 hours to accomplish this. Once Lowland Point was cleared, the vessel operated in the continuous mode as far as Northwest River through ice ranging in thickness from 0.53 m in the east to 0.41 m west of Epinette Point.

On the outbound voyage, the MACDONALD retraced the refrozen inbound track and averaged a speed of 9.1 knots as compared with 2.1 knots inbound.

Through the pack ice during the inbound voyage, the ice was of varying thickness and concentration with the heaviest ice being experienced in a 35-mile stretch in the vicinity of 53°00'N, 55°28'W. The ice was of 10/10 concentration with thicknesses of 0.20 m to 0.38 m. Ridging was severe and covered approximately 3/10 of the area and the entire mass was under heavy pressure.

Ice in Groswater Bay was generally 0.15 m thick and was traversed at an average speed of 12.4 knots.

On the outbound voyage, the 240 miles between the head of Groswater Bay and the Strait of Belle Isle were covered at an average speed of 14.6 knots.

2.3.7 April, 1972

In mid-April, 1972, the CCGS LOUIS ST. LAURENT undertook a probe to Lake Melville via the Strait of Belle Isle but was forced to terminate the mission when it became beset in extremely heavy ice in the Labrador Sea 100 miles southeast of the entrance to Lake Melville (Bradford, 1979). Ice thickness measurements taken in the area were sometimes in excess of 2.4 m and the average thickness was 1.6 m. An aerial ice reconnaissance revealed that similar conditions existed for 70 miles

ahead of the ship and the captain estimated that 5 days of continuous butting would be needed to reach Lake Melville with two more days to reach the western end of the lake. Because of the possibility of running out of fuel on the return voyage if the probe had continued, it was decided to terminate the probe.

In addition to being influenced by greater than normal ice thicknesses, the LOUIS ST. LAURENT was noticeably slowed when winds were onshore even though the maximum wind speed recorded was 22 km/hr. During onshore winds, the ship averaged a speed of only 0.9 knots as opposed to 2.6 knots during the offshore wind. The author suggests that it is doubtful that the probe would have reached as far north as it did if it had been escorting a merchant vessel. The ST. LAURENT was continually deflected off its course by massive floes, and changes in the course were so frequent and sudden that the track would have been difficult for an escorted vessel to follow.

2.3.8 December, 1972

In December, 1972, the JOHN A. MACDONALD, JOHN CABOT and SIR HUMPHREY GILBERT were assigned to provide assistance to two commercial vessels that were icebound in Goose Bay. Freeze-up during this winter was one of the worst on record and is described in detail in Section 3.3.2.1 of this report. The attempt to return the commercial vessels to open water was not successful, and they were forced to stay in Goose Bay over the winter. The GILBERT did, however, help to extricate the CHESLEY A. CROSBIE from the ice near Eskimo Island during this time. This was

accomplished by having the GILBERT advance stern foremost towards the stranded vessel.

2.3.9 May, 1973

During this probe by the MACDONALD, it is reported that the ice at the eastern end of the lake, while appearing to be continuous, was actually pockmarked by holes and areas of weak and rotten ice. From Eskimo Island to Gull Island, the thickness varied from 1.1 m to 2.2 m, and portions of the ice were water covered to areas of up to 10 m². Further into the lake, areas of dark ice and open water 40 to 50 m² were experienced in places, although in many cases the ice was quite heavy. Often, fairly smooth surface features were underlain by ridge keels 2.2 m to 3 m thick. More heavily ridged areas which had not undergone the same surface ablation revealed keels more than 4 m thick. A profile of solid ice 1 m to 1.5 m thick indicated that the top 1/3 was soft, the middle 1/3 hard and the bottom 1/3 soft. In ridged areas the top 2 m to 3 m were hard and the underlying structure comprised loose blocks.

It is noted that the track created on the lake by the JOHN A. MACDONALD during December, 1972 provided less resistance than the previously unbroken ice although the thicknesses were apparently similar. (See Section 6.3 for further discussion on this point.) It was found that crack propagation upon impact was more pronounced in hard, uniform ice providing open water was within 100 to 175 m of the ship while for distances greater than this, the ice provided greater resistance to breaking.

Continuous shore cracks existed around the lake from Eskimo Island to St. John Island and other cracks ran in a north-south direction between Gull Island and the south shore and from Charley Point to Acadia Island. The ice thickness in the vicinity of the latter crack near Green Island was 1.8 m. Westward from a line north-south from Julia Point, the lake was completely ice free.

Because the ice was landfast, problems were experienced with moving the ice past the ship. In the vicinity of ridges, the track was widened to four to five times the ship beam in order to allow the ice to be transferred from stem to stern. In terms of ship progress, the greatest problem was the frequent occurrence of "dry docking"; that is, the ship becoming hung up on the ice. Of the total time required to navigate the ice approximately 20 percent was spent stranded (15 hours, 15 minutes) and approximately 30 percent was spent navigating stern foremost (25 hours, 15 minutes). The average number of rams per hour either ahead or astern was 10.5 for an estimated average gain of 45 m per ram. The average progress through the ice between Eskimo and St. John Islands for the time during which progress was made was 0.33 knots, much of this being accomplished while navigating stern foremost. A similar speed could not be calculated for movement through ridges because the course and ship performance were too irregular. It is noted that in one ridged area, six hours elapsed without any forward gain while the ship opened a large area and detoured around thick pieces of ice to find an easier path.

2.3.10 Discussion

Of the nine icebreaker operations described above, five were successful in that the ship reached the western end of Lake Melville. Only the LOUIS ST. LAURENT (ironically the largest Canadian icebreaker) was not successful in reaching the lake at all, the other unsuccessful missions being terminated in the eastern end of the lake. Only one probe has been reported during the middle of winter, that involving the MACDONALD which in this case reached only as far as Haines Island. The successful probes have taken place either early or late in the season when the ice is not thick enough to cause undue problems or is in a state of deterioration. However, even during these times, it can be seen from the above descriptions that a considerable effort was required to traverse certain heavy portions of the lake, the average speed during such instances being reduced to less than 1 knot and the ship being required to operate for long periods in the ramming mode. During the January, 1972, probe, it was seen that the MACDONALD had no problem steaming continuously in uniform ice of average thickness 0.36 m and 4.6 knots in ice 0.41 m to 0.53 m thick, however, in rough ice averaging 0.69 m, a total of 16 hours was required to advance 22 km. It thus appears that the continuous capability of the MACDONALD at a reasonable speed (in the order of 3 to 4 knots) in non-pressured, solid ice is in the order of 0.6 m. A vessel with this capability could extend the navigation season in Lake Melville possibly 1-1 1/2 months beyond the present closing date in late November. Likewise, considering the deteriorated state of the ice cover in late spring, the season could be opened a few weeks early on the average than is presently the case.

Extensions of the season beyond mid-January and prior to early May would have to take heavier pack ice conditons and thicker and/or more solid lake ice into consideration. A more capable ship than the JOHN A. MACDONALD would be required to negotiate such ice conditions.

3. STUDY AREA ENVIRONMENT AND HAZARDS TO NAVIGATION

3.1 Introduction

In this section of the report, a detailed description of the environment of the study area is presented. This description attempts to address all the environmental factors which would influence vessels operating year-round in the Labrador Sea, Groswater Bay and Lake Melville. In addition to describing the pertinent features of the area, analyses of the freeze-up and breakup processes of the ice on Lake Melville are carried out. The freeze-up analysis is especially important since it identifies the major factors which cause particular ice conditions on the lake during any season. In order to illustrate the differences in freeze-up patterns over a number of years, on-ice measurements, satellite imagery, ships' logs and meteorological conditions have been studied for the period 1972-1978, and freeze-up during these years is discussed in some detail.

The pack ice conditions are of obvious, special importance to this study, and several sources of information have been used in the documentation of these conditions. As mentioned earlier in this report, the AES Ice Central Charts were used to obtain ice conditions for eleven years, and these conditions were used to determine the performance of vessels traversing the pack. These charts were also analysed for information on the frequency of multi-year ice, ridging, leads, snow cover and other features in the pack, although the charts are limited in this regard. Radar imagery from overflights of the pack and satellite imagery were also studied in an attempt to obtain further information

on these features. In addition to these sources, published reports on the study area were used whenever appropriate. Finally, the consultant's experience in the study area was used to provide some uniformity to the findings from the above sources. However, as will be evident to the reader, from the information that is presently available, it is often difficult to quantify specific characteristics of the Labrador pack ice and often only a qualitative description is possible.

3.2 Bathymetry and Oceanography of Lake Melville and Groswater Bay

Lake Melville and Groswater Bay comprise the largest inlet along the coast of Labrador. Groswater Bay gradually narrows over a distance of 56 kilometers from about 35 kilometers at the mouth to approximately 1 1/2 kilometers at the Narrows. The Narrows, separating Groswater Bay from Lake Melville, has a sill depth of 30 metres and extends for about 10 kilometres to where Henrietta Island divides it into two channels (Figure 1.1). The tidal currents in The Narrows are very strong with the velocity of flood ranging from 2 to 3 1/2 knots and the velocity of ebb ranging between 3 1/2 and 5 1/2 knots. The duration of ebb tide is longer than that of flood. The duration of ebb is on the average 6 hours 67 minutes while that of flood is 5 hours 38 minutes.

The channel westward of Henrietta Island is the channel usually used for transportation because the cross-currents are not as strong as in the eastern channel known as Pike Run. A group of islets lie in the southern entrance on the eastern side of Pike Run. These islands and shoals combined with tide rips and whirlpools make this entrance very dangerous for the passage of large ships.

The channel west of Henrietta Island is further divided by Eskimo Island in the middle of the southern entrance. The channel east of Eskimo Island is usually used due to its greater depth. It has a minimum depth of 18 meters, whereas the west channel has a depth of approximately 9 meters. The tidal currents in both channels have a speed ranging from 3 to 6 knots during flood and 4 to 6 knots during ebb. Heavy tide rips and whirlpools occur in these channels, and are most severe during spring tides.

Lake Melville extends about 140 kilometers from Pike Run at The Narrows to the head of Goose Bay. The width varies from about 3 kilometers at the entrance to a maximum width of more than 30 kilometers near its southwestern end. The lake has a basin depth of over 200 meters. There are several islands near the east end which tend to stop the drift of ice during the prevailing southwest winds. The existence of these islands tends to aid the formation of ridges in this area during the time of freeze-up. The west end of Lake Melville is fronted by many small islands and shoals, but there is a deep channel extending into Northwest River and to Sandy Point at the entrance to Goose Bay. Goose Bay is a 20 kilometer extension of Lake Melville with an average width of 8 kilometers and a basin depth of over 65 metres.

The restriction of The Narrows dampens the rise and fall of the tide from 1.3 to 2 metres just outside the Narrows to 0.4-0.7 metres in Lake Melville. The tide in this area is mainly semi-diurnal. There is a phase lag of approximately 4 hours between the time of high and low water between Groswater Bay and Lake Melville.

The surface currents within Lake Melville are variable due to tides, wind, and the fresh water discharge from the Churchill, North-west, Kenamu and Goose Rivers. The water discharge maintains a low salinity brackish water near the surface throughout the year, causing the formation and growth of ice to be different than for normal sea ice.

3.3 Ice Freeze-up and Breakup on Lake Melville

3.3.1 General description of the freeze-up process

The surface water in Lake Melville begins to cool during September. The quantity of heat that must be extracted before ice formation can begin depends mainly upon the hydrographic structure of the water. During the Blue Dolphin Labrador Expeditions, Nutt (1951) found that the salinity of the surface water during August varied from 3.0 parts per thousand off Epinette Point to about 10.0 parts per thousand west of St. John Island with the halocline occurring between depths of 10 and 20 metres. The temperature of maximum density for water of salinity 10⁰/00 is +1.84°C while the freezing temperature is -0.53°C. This means that by mid-September when the air temperature is usually below 2°C, thermohaline convection becomes a prominent mixing process, thus cooling the surface layer.

Hydrographic measurements taken during the Blue Dolphin Expeditions indicate that this cooling process extends to a depth of approximately 10 metres only. This is shown by bathythermographs of Lake Melville during March 1953 which show a warm wedge of water between depths of 5 and 10 metres with the temperature varying between 1°C and 2°C. An

interesting point is that the salinity at a depth of 10 metres was approximately 24.5⁰/oo, the limit for which the temperature of maximum density is reached before the freezing point. Once the upper 10 metres of water becomes mixed, further cooling causes the surface water to become lighter than the sub-surface water and convection is reduced.

At a temperature of -0.5°C, ice formation will begin where the water is relatively calm. Since the first few meters of water are usually being mixed by the action of wind and waves, supercooling will initiate the formation of frazil particles. As the frazil particles increase in size, they agglomerate to form slush, float on the surface and refreeze to form the first layer of ice. The frazil particles in Lake Melville are deposited first in protected areas along the shore. The pattern of freeze-up for the rest of the Lake is variable and depends mainly on the wind conditions which move the slush and ice pans around until they consolidate.

The waters of Goose Bay are much less saline than the waters of Lake Melville and thus require less cooling to reach freezing temperature. In addition, the geometry of the bay restricts the movement of slush and ice pans and, as a result of these two factors, Goose Bay tends to be frozen over while ice is just beginning to form in Lake Melville.

Once the ice cover in Lake Melville becomes consolidated there exists a fresh layer of water in the boundary layer between the ice and the more saline tidal water. Since the ice will be produced from

practically fresh water, the growth will be slightly higher than that for sea water. This fresh layer of water in fjords is cooled from below as well as from the atmosphere. When saline water cooled to near its freezing point flows under fresh or brackish water also cooled to near its freezing point, there is an additional heat transfer from the fresh water to the saline water. McClimans (1978) showed from laboratory experiments that the heat loss to the lower layer is a maximum when the salinity of the lower layer is approximately 18⁰/oo. Weak currents will enhance the ice growth rate by this process, whereas strong currents will induce considerable mixing and thus reduce the growth rate.

The maximum thickness of the unconsolidated ice pans and slush before freeze-up can be determined by the salinity distribution in the ice cover. The surface water in fjords is always brackish, but once a complete ice cover has formed, the water in the boundary layer directly below the ice exhibits a very low salinity ranging from 0 to a few parts per thousand. This phenomenon is evident in the water salinity measurements made in Lake Melville during March 1953 during the Blue Dolphin expedition (Coachman, 1953).

Salinity measurements of ice cores during the 1979 field survey of Lake Melville indicate that the ice pans and slush were approximately 0.65 metres thick off Cabot Island at the time of complete freeze-up. This value is high because the autumn of 1978 experienced high winds which prevented consolidation while the ice continued to grow.

Due to the lack of in-situ ice data, the time of freeze-up for the last seven years in Lake Melville was determined by a combination of satellite imagery, ship logs, and meteorological records. There is an extensive amount of data available for Terrington Basin, but due to its shallow depth, size and topography and low salinity (approximately 1⁰/oo) the dynamics of freeze-up are completely different from that of Lake Melville. Formation of ice in Terrington Basin occurs within one week after subfreezing temperatures are recorded (Lee, 1955). A comparison between the dates of complete freeze-up in Terrington Basin and Lake Melville for the last seven years (1972/73 - 1978/79) shows that the dates differ by 10 to 50 days. Clearly, the date of freeze-up in Terrington Basin cannot serve as an indicator for the date of freeze-up of Lake Melville.

The meteorological measurements at Goose Bay were compared with information from satellite imagery and ship logs. This comparison indicates that the wind conditions during the time of ice formation were the main factors responsible for the formation of ridges. The larger ridges appear to have been formed in the late stages of freeze-up when there was a substantial amount of ice present. The location of the ice ridges cannot always be predicted from wind observations at Goose Bay because a Northwest wind on the lake may be recorded as a Southwest wind at Goose Bay airport due to the topography of the surrounding area.

The patterns of freeze-up in Lake Melville for the last seven years are described in the following section.

3.3.2 Freeze-up Description for 1972-1978

3.3.2.1 Freeze-up 1972

Freeze-up in Lake Melville during the fall of 1972 has been well documented by Memorial University in studies referred to earlier in this report. Further data are available through satellite imagery and from cruise reports from the CCG icebreaker SIR HUMPHREY GILBERT.

Goose Bay was completely frozen over by November 8 with an ice thickness ranging between 2.5 cm and 5 cm. Pans and floes between 7.5 cm and 10 cm thick covered more than half of Lake Melville by late November. The loose ice was concentrated in the eastern half of the lake on November 26 (Figure 3.1). This distribution pattern probably resulted from the high westerly winds recorded at Goose Bay on November 22 with velocities ranging between 27 and 42 km/hr.

Ice conditions observed from the SIR HUMPHREY GILBERT on December 2 were as follows:

- (a) 10/10 pancake ice north of Adams Point
- (b) significant open water in the vicinity of Eskimo Paps
- (c) broken large pan ice in the vicinity of Green Island.
- (d) heavy ice south of Eskimo Island

The ice pans ranged in thickness from 5 cm to 30 cm, and thus were liable to intense deformation and failure as a result of the storms which occurred in the area between December 2 and 4. Winds were recorded by the SIR HUMPHREY GILBERT at Rigolet to be from the west and southwest with speeds between 64 and 105 km/hr. The winds at Goose Bay

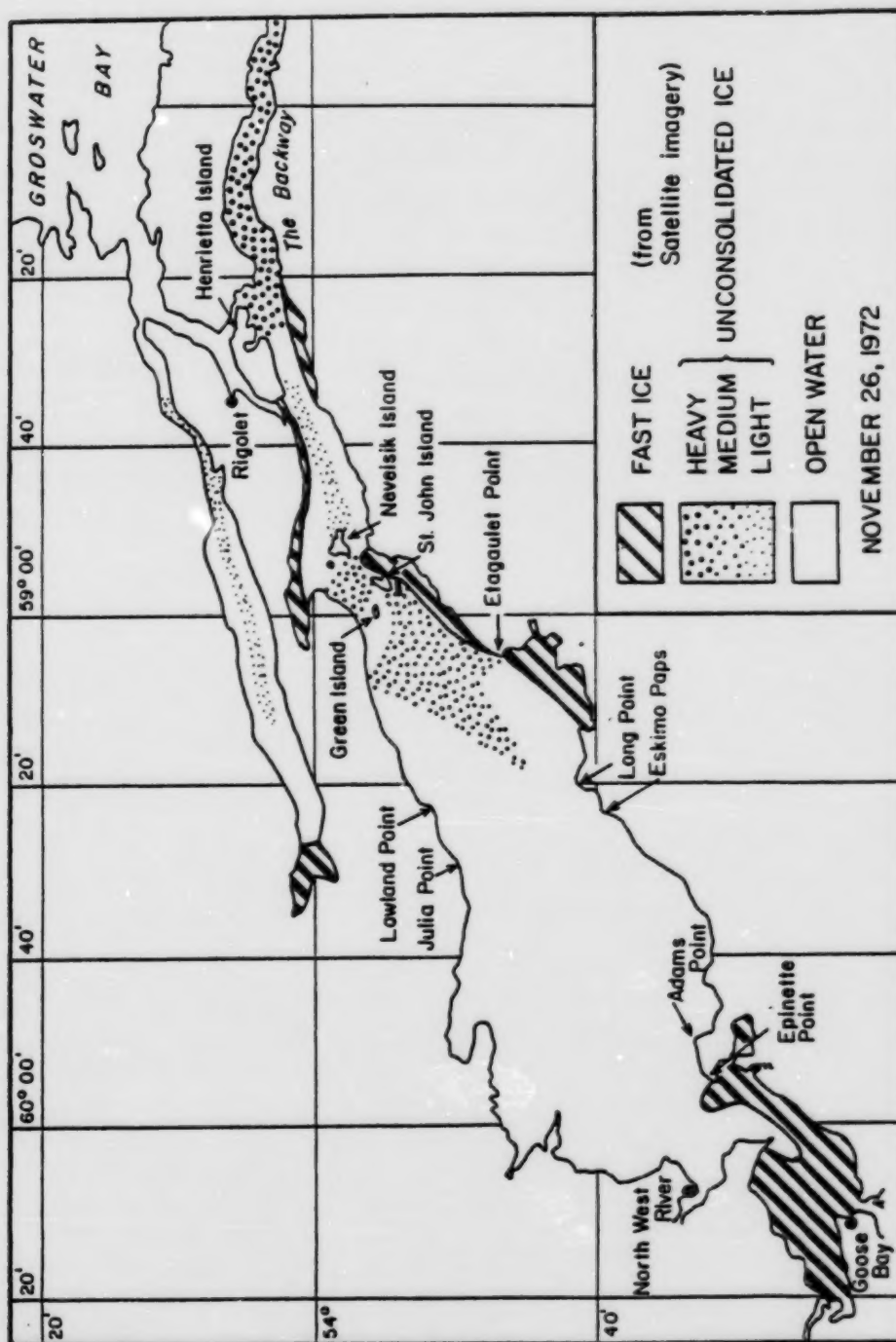


FIGURE 3.1 SKETCH OF FREEZE-UP ICE CONDITIONS

were recorded as being 22 to 61 km/hr with gust to 106 km/hr. On December 5 an aerial survey by Memorial University showed extensive rafted ice in the east end of the lake. The edge of the rafted ice lay just west of St. John Island (Figure 3.2). Rafted ice also occurred along the south side of the lake, indicating that the wind on the lake was likely to have been from the northwest for a significant amount of time. The ice remaining in the middle of the Lake on December 5 was still mainly unconsolidated. There were areas of open water in the west end with a belt of shorefast ice approximately 1.2 km wide north of Northwest River to Mulligan Bay.

Strong west winds occurred again on December 7 with a maximum hourly speed of 48 km/hr recorded at Goose Bay. This produced a further extension of the rafted ice edge from near St. John Island to the area between Lowland Point and Etagaulet Point. By December 13, Lake Melville had completely frozen over. The distribution of rafted ice and ridges on this date is shown in Figure 3.3. This was an exceptional year because three major storms occurred late in the freeze-up period.

3.3.2.2 Freeze-up 1973

In addition to satellite imagery and meteorological data, freeze-up information for Lake Melville in 1973 is available from aerial reconnaissance carried out by Memorial University on December 9, 13, 19, 20 and January 25 to 31.

Goose Bay was partially frozen over and fast ice existed around the shoreline of Lake Melville on November 22. By December 9, Goose Bay was

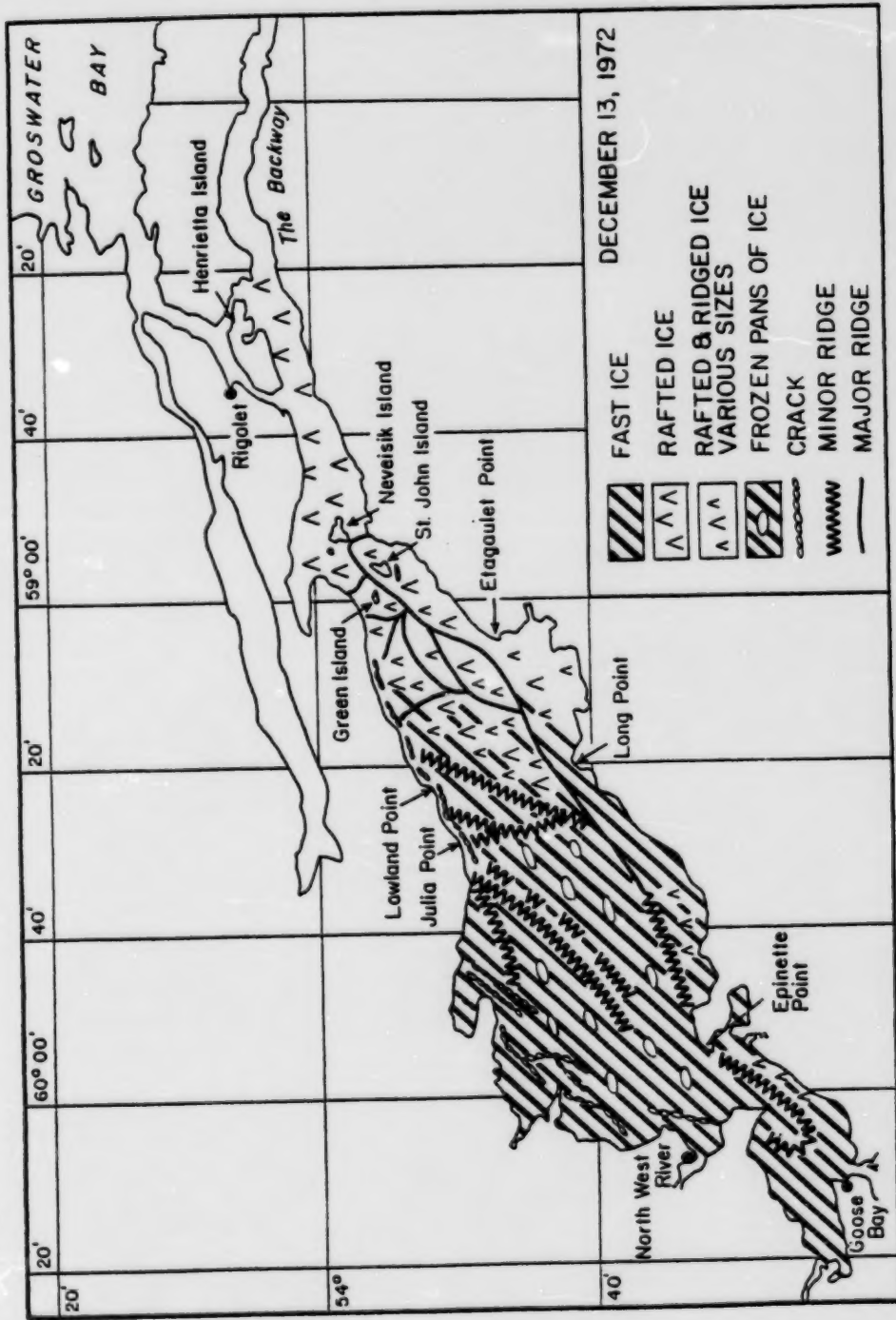


FIGURE 3.3 SKETCH OF FREEZE-UP ICE CONDITIONS FROM AIR PHOTOGRAPHS

almost completely frozen over and patchy ice existed in Lake Melville from just west of Henrietta Island eastward into *The Backway* (Figure 3.4). Patchy ice also occurred around St. John and Neveisik Island. The ice pattern during the early stages of freeze-up was similar to that in 1972. The loose ice was concentrated in the east end of Lake Melville due to strong winds which occurred between November 26 and December 1 and again on December 7 when there was a west-southwest wind of 48 km/hr recorded at Goose Bay.

By December 20, ridged, consolidated ice covered the area from the west end of Henrietta Island eastward into *The Backway*. The remainder of Lake Melville, except for the protected bays and near-shore areas, was reported to be either open water or under mobile ice cover.

On December 27, the central part of the Lake was covered by loose, thin ice with a heavier concentration on the south side (Figure 3.5). Again, as in 1972, strong west and southwest winds occurred during the late stages of freeze-up. Winds on December 19 and 20 reached a speed of 45 km/hr and during a storm between December 23 and 25, winds reached a speed of 61 km/hr. Another storm on December 31 produced west-southwest winds of 56 km/hr. By January 3 the sub-freezing temperatures of -30°C had caused the ice to become completely consolidated.

The low-level aerial reconnaissance by Memorial University between January 25 and 31 reported the following observations:

- (a) an essentially flat ice cover with occasional rafting to the west of a line from Julia Point to Long Point;

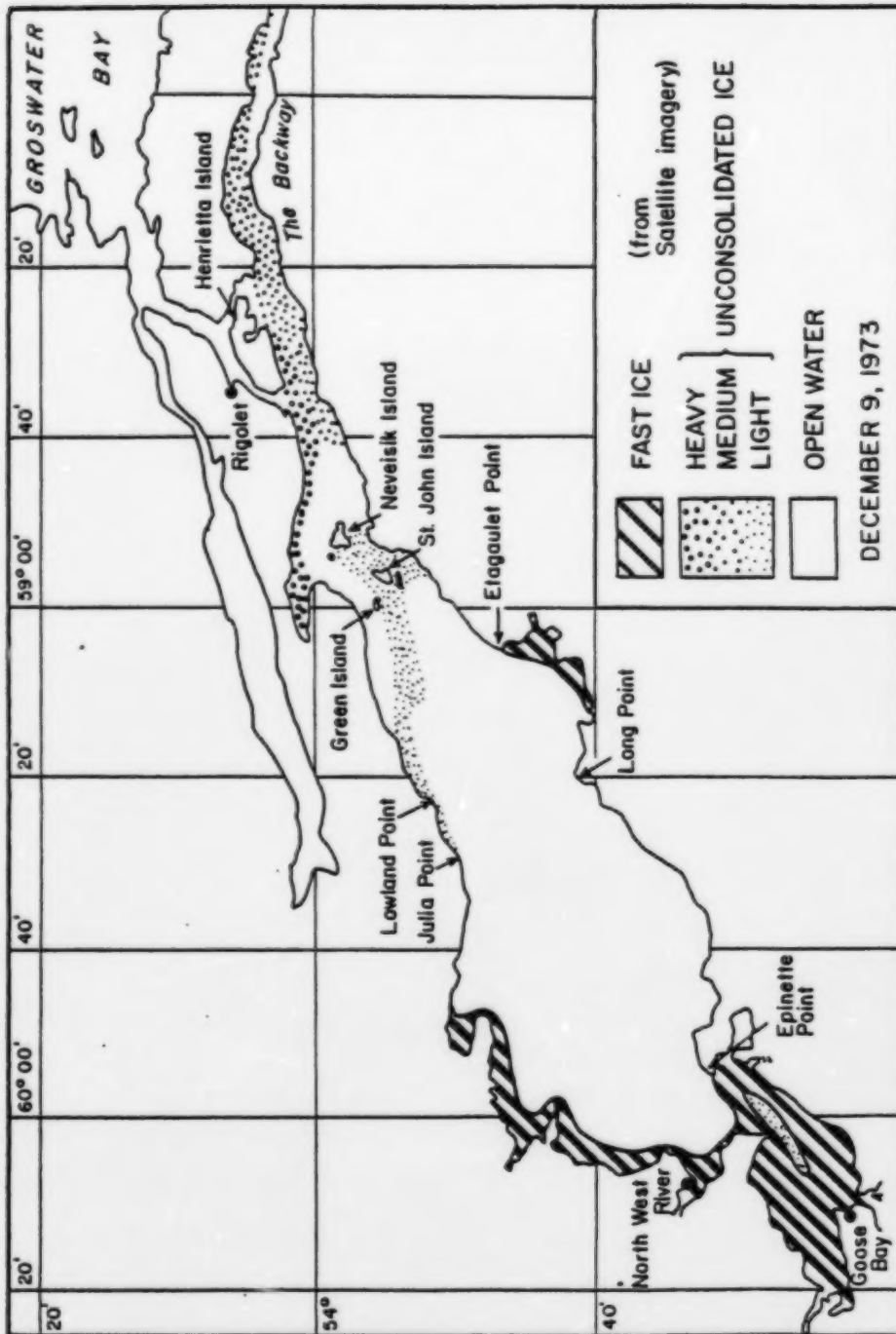


FIGURE 3.4 SKETCH OF FREEZE-UP ICE CONDITIONS

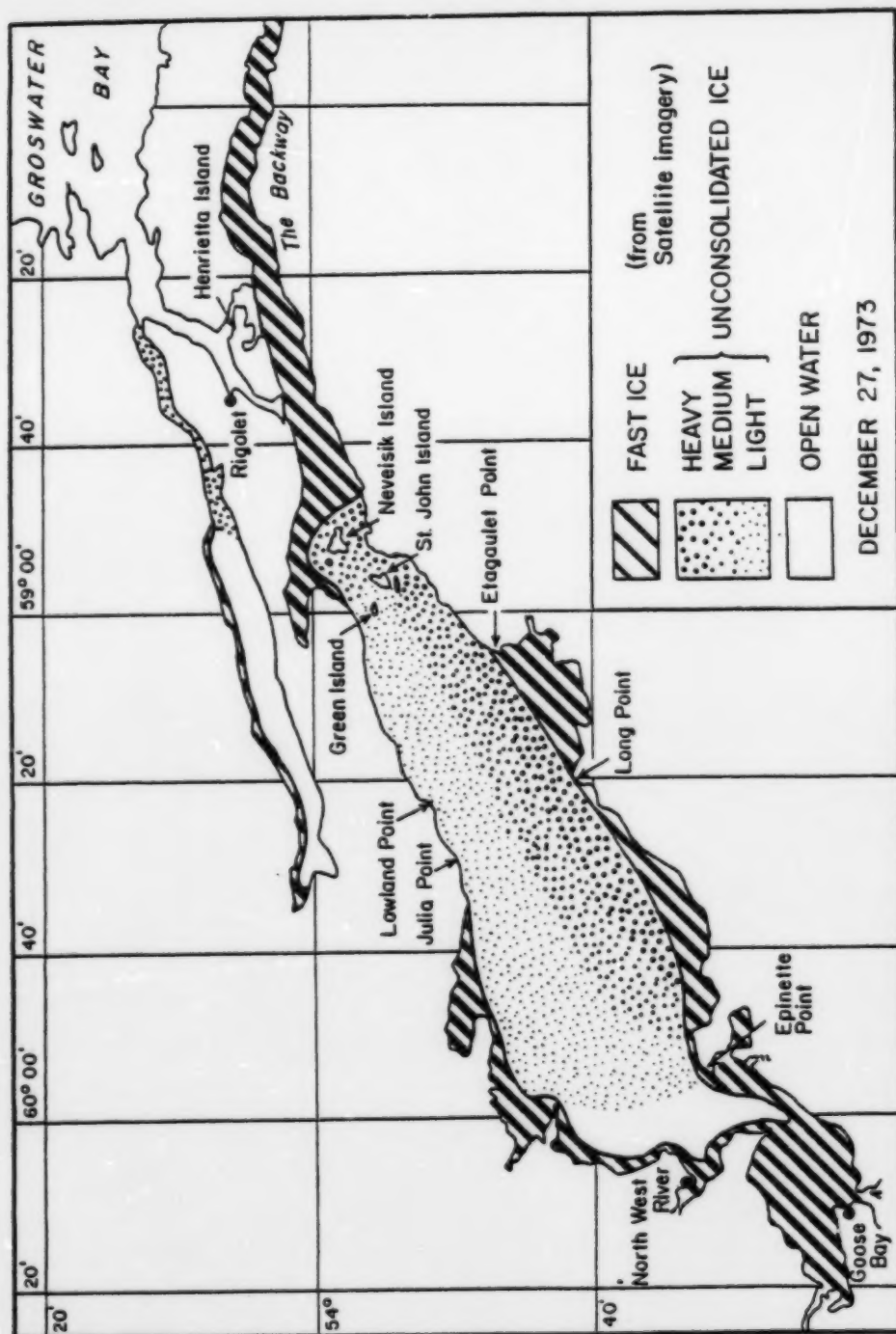


FIGURE 3.5 SKETCH OF FREEZE-UP ICE CONDITIONS

- (b) an increased degree of rafting abeam of Lowland Point;
- (c) a noticeable boundary to more rafted ice just east of Etagaulet Point;
- (d) the most prominent ridge extending from Charley Point to just south of Green Island.

3.3.2.3 Freeze-up 1974

The only information available on ice conditions in Lake Melville in the fall of 1974 is from satellite imagery and no imagery data are available in the period from December 5 to January 9.

The formation of ice in Lake Melville in 1974 occurred during relatively calm weather. The first period of major cooling began near the end of November. Goose Bay had completely frozen over and fast ice existed in the protected bays along the shore by December 5. Due to cloud cover, no data are available for the eastern half of the lake on that date. This stage of freeze-up in Goose Bay indicates that The Backway was probably also frozen over by December 5. The most critical time for the formation of ridges would have been from December 5 until the ice consolidated. Consolidation likely occurred during the period from December 13 to December 17 when the average temperatures ranged between -8 and -22°C. This whole period was extraordinarily calm with the maximum wind velocity occurring on December 9 with a speed of 32 km/hr from the south, a direction not likely to cause significant ridging due to the short wind fetch. Low temperatures and calm weather persisted throughout December. Satellite imagery shows that the Lake

was completely frozen over on January 9. However, the ice was no doubt consolidated prior to that date. The type of ridging which occurred during the previous two years did not have the opportunity to form during the fall of 1974.

3.3.2.4 Freeze-up 1975

Satellite imagery and meteorological data are the only sources of information available on freeze-up in Lake Melville during the fall of 1975. Goose Bay was completely frozen over, and landfast ice existed around The Bight and Epinette Peninsula on November 30 (Figure 3.6). Loose ice was apparent off Rabbit Point. No data are available for the eastern part of the lake on that day. Low temperatures, fluctuating around -15°C , prevailed during the week preceding November 30 and winds were relatively low. Most of the ice observed on November 30 would have formed during this period. High winds were recorded on November 20 and 21 from the westnorthwest at 60 and 56 km/hr respectively and on November 23 from the westsouthwest at 56 km/hr. These winds could have caused ridging near The Backway if enough ice were present during that time. However, it is unlikely that any significant amount of ice was present because the ship's log of the TANA WOODWARD on November 18 reported soft ice of only 5-7.5 cm thick in Terrington Basin which freezes before The Backway.

High winds were recorded from December 1 to 4. Winds reached a maximum of 40 km/hr from the south-southwest on December 1 and 32 km/hr from the west and southwest on December 2 and 4. These winds would have

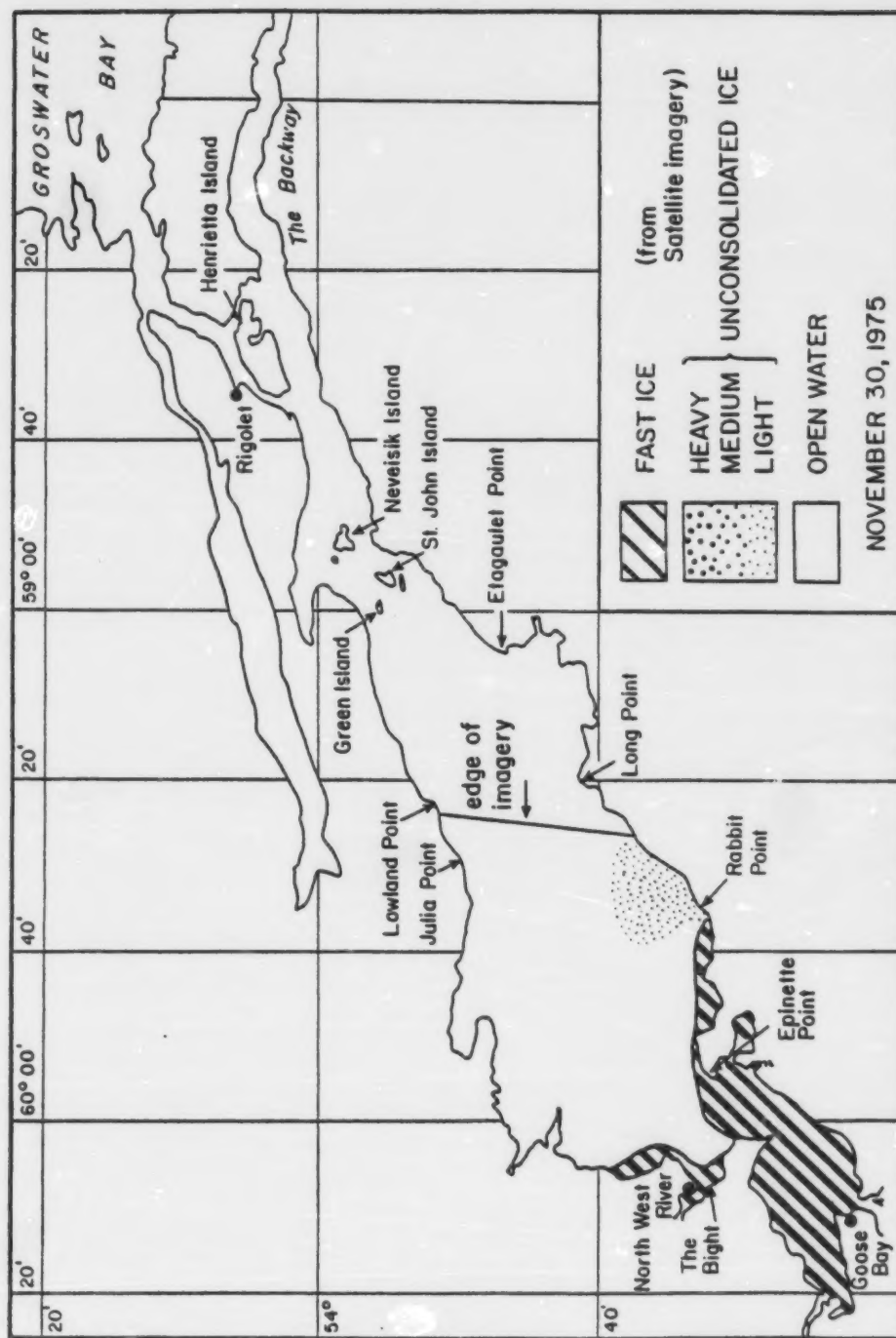


FIGURE 3.6 SKETCH OF FREEZE-UP ICE CONDITIONS

caused the ice to become concentrated in the east end of the Lake. By December 9, the formation of heavy unconsolidated ice had progressed to a line between Lowland Point and Long Point (Figure 3.7) while loose ice was evident over most of the remaining area of the Lake. Low temperatures with average values between -5°C and -24°C prevailed the following week during which time the ice most probably consolidated.

3.3.2.5 Freeze-up 1976

Freeze-up information for Lake Melville in 1976 is available from satellite imagery and ship logs from the TANA WOODWARD and the CCGS SIR HUMPHREY GILBERT.

Fast ice was reported in Goose Bay on November 25 by both the TANA WOODWARD and the SIR HUMPHREY GILBERT but there was mainly open water on Lake Melville. On November 28 the SIR HUMPHREY GILBERT reported: (a) 10/10 fast ice 23 cm thick in Goose Bay Narrows and approaches; (b) fast ice 5 cm thick off Epinette Point and (c) consolidated ice 10 cm - 15 cm thick across the western end of Lake Melville.

Loose ice existed at the eastern end of the Lake on December 1 with stretches of open water between Neveisik Island and The Backway (Figure 3.8). Freeze-up progressed from west to east in 1976 instead of in the usual east-west direction. Strong northeast winds prevailed from November 19 to 21 with a speed of 57 km/hr with gusts to 80 km/hr which would have moved the loose ice in the lake to the western end. On November 24 and 25, the wind was from the westsouthwest with a maximum

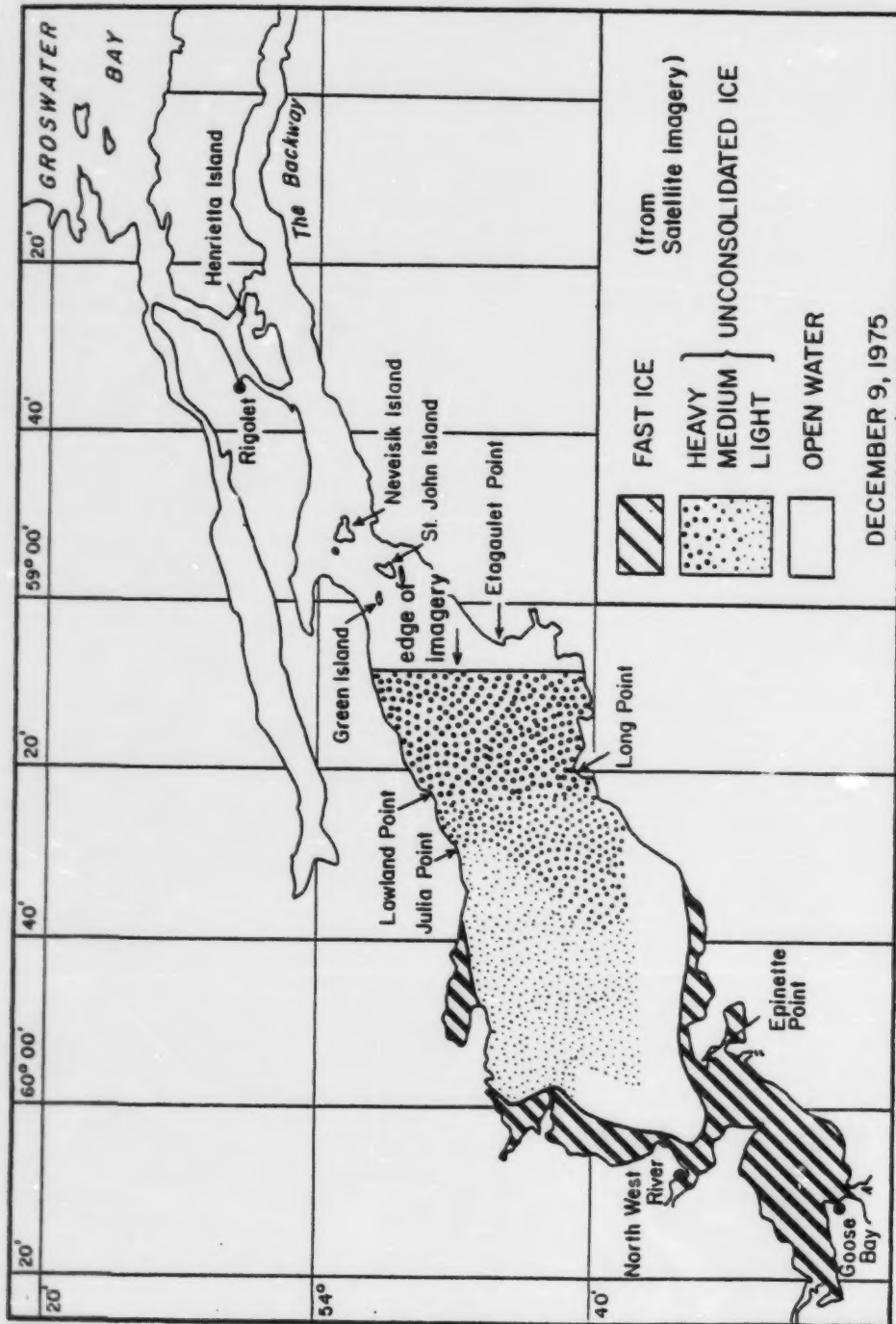


FIGURE 3.7 SKETCH OF FREEZE-UP ICE CONDITIONS

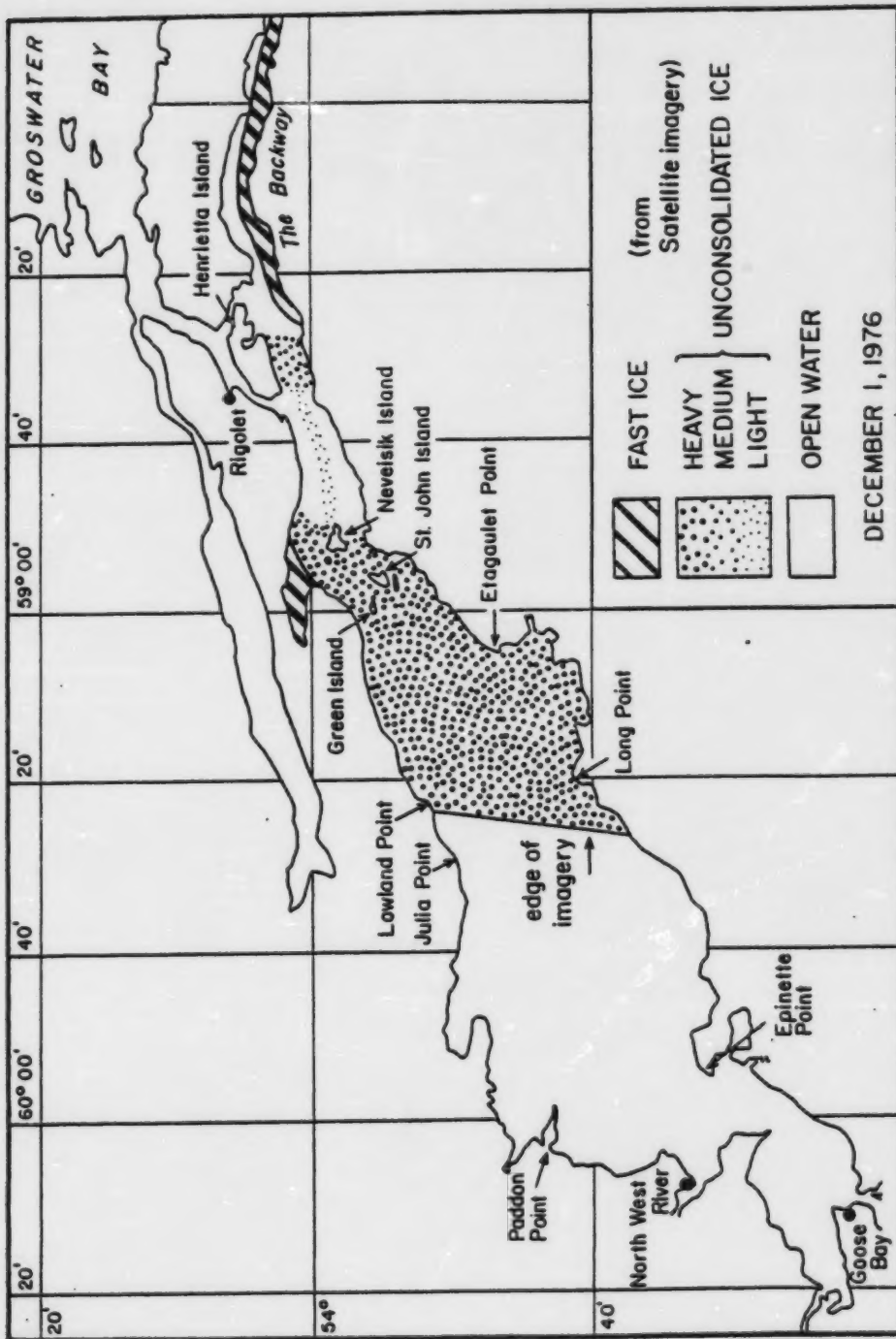


FIGURE 3.8 SKETCH OF FREEZE-UP ICE CONDITIONS

speed of 33 km/hr. However, apparently the ice remained in the west end and this section of the lake consolidated during cold temperatures (-15°C) between November 25 and 28.

Strong winds reaching speeds of 65 km/hr gusting to 96 km/hr between December 3 and 6 may have caused ridging at the east end of the lake since the ice in that region had not completely consolidated. Complete consolidation of the lake likely occurred shortly after this storm.

3.3.2.6 Freeze-up 1977

Satellite imagery and meteorological data were used to determine the freeze-up pattern of Lake Melville in 1977. Some direct observations of ice conditions were made by Ice Engineering Limited, St. John's in April 1978.

Consolidated ice existed in Goose Bay on November 15. On November 26, the satellite imagery shows loose unconsolidated ice west of St. John Island and east of Neveisik Island with open water between the two islands (Figure 3.9). Winds from the southwest reached a speed of 43 km/hr during the period November 28 to December 1. These winds would have caused the ice to concentrate in the east end of the lake and were probably strong enough to cause ridging. No significant amount of ridging was likely formed because freeze-up was still in the early stages. However, this wind most likely formed the hummocked ice field west of St. John Island as observed by Ice Engineering Limited.

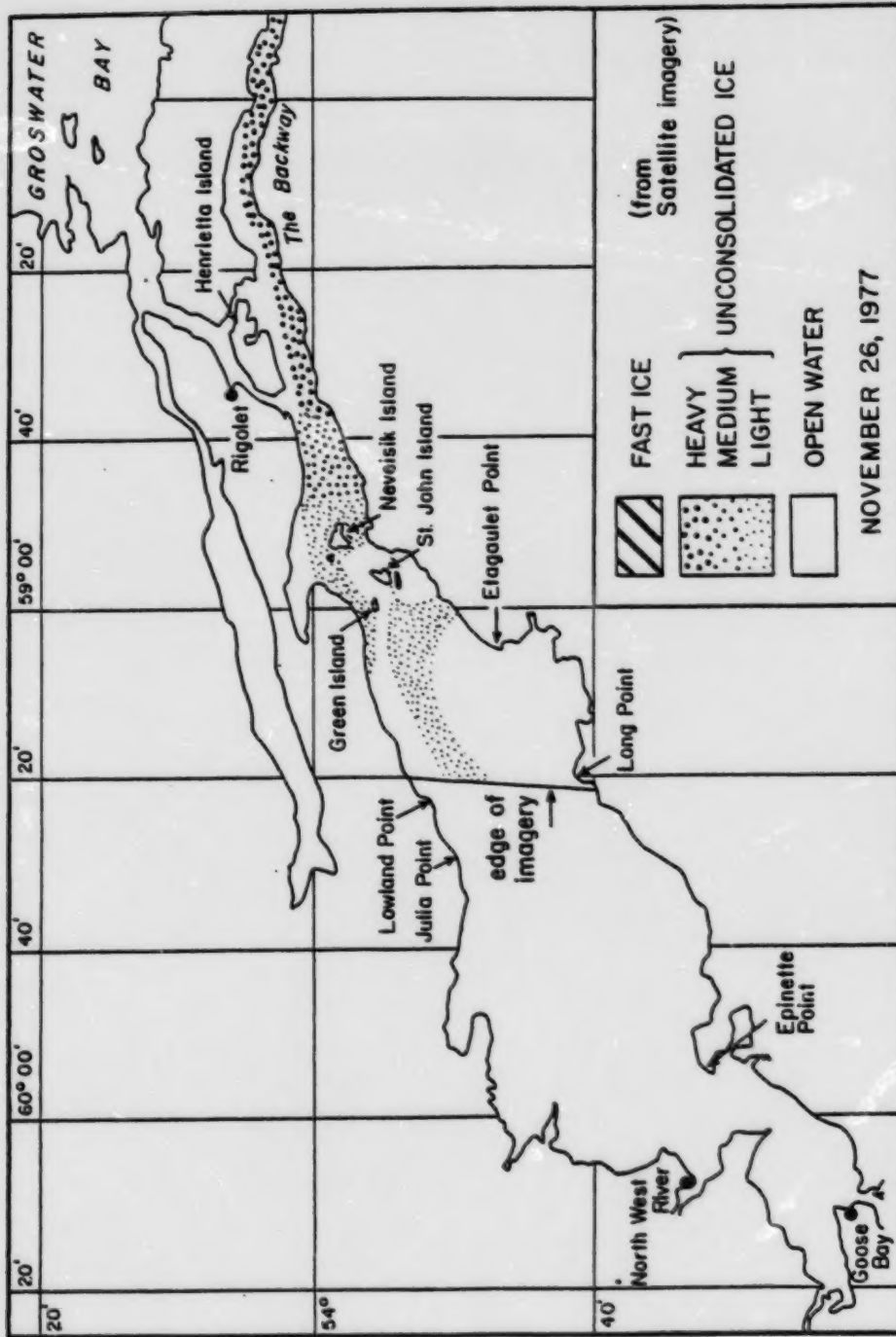


FIGURE 3.9 SKETCH OF FREEZE-UP ICE CONDITIONS

The majority of unconsolidated ice probably formed during the relatively calm period between December 2 and 9. On December 10 and 11, a storm from the northwest produced winds of 82 km/hr gusting to 111 km/hr and air temperatures reached a maximum of approximately -20°C. This storm likely produced the hummocked ice field reported between Etagaulet Point and Rabbit Point in April, 1978 by Ice Engineering Limited. The lake probably completely consolidated in the week following this storm when the temperature had a mean value of approximately -22°C.

3.3.2.7 Freeze-up 1978

Freeze-up information for 1978 is available from satellite imagery, the log of the AMBROSE SHEA and a field survey conducted as a part of the present study.

On November 23, the ice appeared from satellite imagery to be solid eastward of a line halfway between Neveisik Island and Henrietta Island (Figure 3.10). Heavy unconsolidated ice extended westward from this line to a line between Long Point and Julia Point. The log of the AMBROSE SHEA reported heavy ice west of Eskimo Island, a rafted bar of ice abeam of Gull Island, and loose ice off Eskimo Paps. The ice formation progressed westward from the east end of the lake because the wind was predominantly from the west or southwest from November 13 to 22 reaching at least 28 km/hr every day with gusts often in excess of 50 km/hr. These winds would have been sufficient in strength to produce ridging during this period of freeze-up.

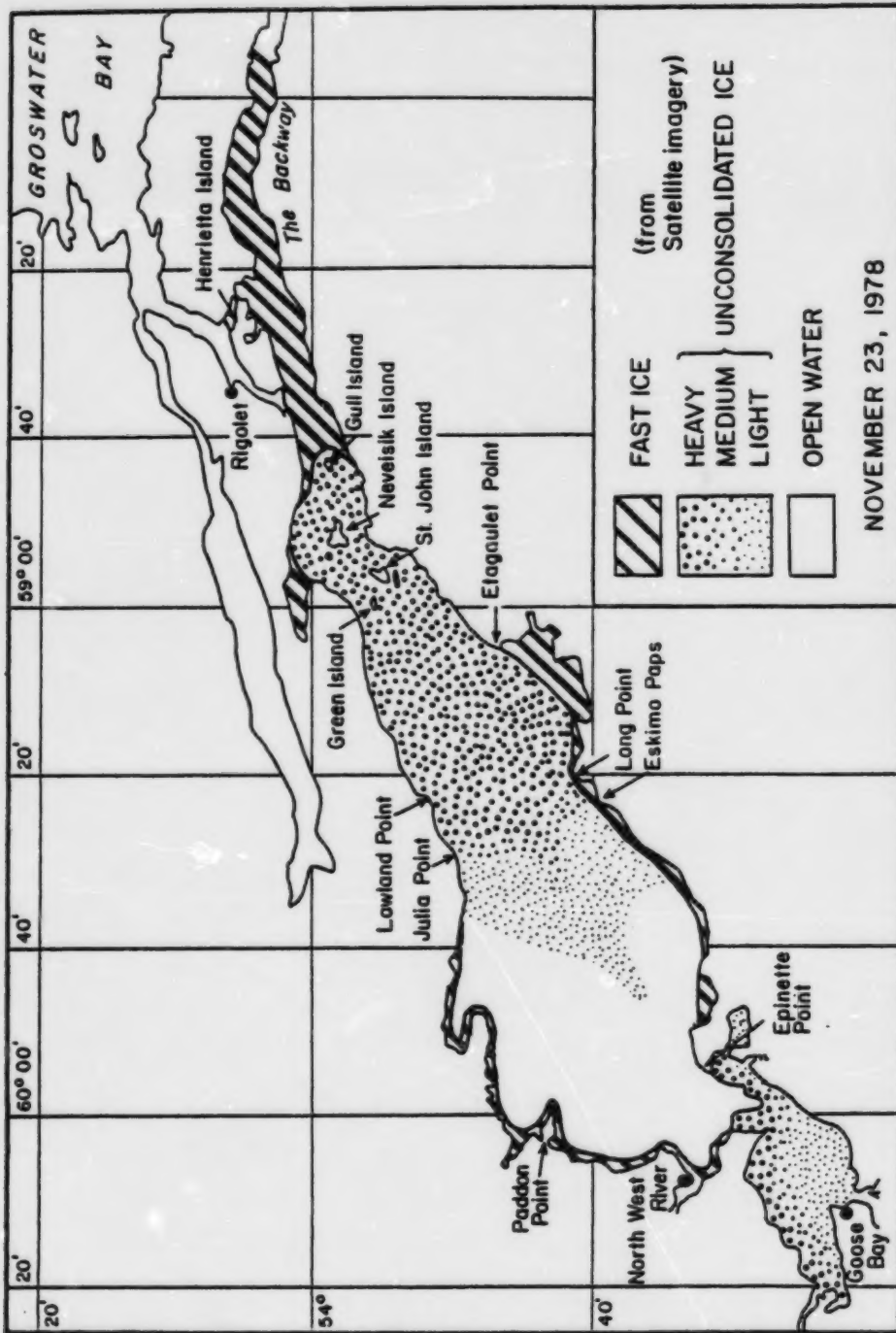


FIGURE 3.10 SKETCH OF FREEZE-UP ICE CONDITIONS

A reconnaissance of the lake on December 9 showed that the lake was completely frozen over by that time. This would have occurred during the last few days of November and the first week of December when the mean temperature ranged between -8°C and -22°C . On November 26 and 27, winds from the northwest and west produced winds of 37 km/hr with gusts to 59 km/hr. This wind probably caused the rafted ice reported off Lowland Point by the AMBROSE SHEA on November 28. West winds of 37 km/hr were also recorded at Goose Bay during December 1 to 3. This wind could have caused rafting or ridging in the far west end of the lake if the ice had not been completely consolidated by that time. The reconnaissance of December 9 showed no indication of heavy ridging on the inner-island channels nor on the main body of the lake. Ice thicknesses were in the order of 0.40 m.

The ice displayed many cracks in the area between Eskimo Paps and Julia Point on December 20 according to satellite photos. This fracturing of ice likely occurred on December 18 during strong winds (50 km/hr) from the northeast and above normal temperatures ($+4^{\circ}\text{C}$).

3.3.2.8 Summary of Freeze-Up Conditions

The description of freeze-up patterns for the seven years from 1972 to 1978 shows that extensive ridging occurred in 1972 and 1973. Since the prevailing winds are from the southwest, freeze-up will generally progress from east to west on Lake Melville. However, it is not uncommon for the opposite pattern to be observed. Ridging is expected to occur more often around St. John and Green Islands due to the blocking

effect of the island during the southwest storms. However, ridges can be found anywhere on the lake depending on the stage of ice formation and the wind direction during a particular storm. The ridges would be of less consequence to navigation in the wider parts of the lake.

From satellite imagery, meteorological conditions and ship logs, the approximate start date for icebreaker requirements in Lake Melville (based on ice conditions) have been estimated for the year 1972-1978 and are shown in Table 3.1 together with the dates of complete ice consolidation.

3.3.3 General Description of the Breakup Process

The ice in Lake Melville usually begins to melt during the first week of May. The melt water flows along drainage patterns on the surface to open water at the shoreline or to holes that develop in the ice cover. When the melt water drains away, the surface most likely has a porous, white and crumbly structure. This is the time of year when spring run-off from the rivers supplies a substantial amount of fresh water. Once the ice cover reaches an advanced stage of melt, the currents created by wind will help break up the ice cover and induce circulation. If the warmer subsurface water in Lake Melville is brought into contact with the ice it can cause rapid weakening. This effect combined with strong winds and increased currents can cause the ice to melt very quickly, often within a couple of days.

In the following sections, the breakup process is described for the years 1973 to 1979.

TABLE 3.1

Estimated start dates for icebreaker requirements
in Lake Melville (based on existing vessel traffic) and the
dates of complete ice consolidation

<u>Year</u>	<u>Date requiring icebreaker</u>	<u>Date complete freeze-up</u>
1972-73	December 2	December 12
1973-74	December 13	January 3
1974-75	December 1	December 15
1975-76	November 30	December 15
1976-77	November 28	December 7
1977-78	November 28	December 12
1978-79	November 23	November 31

3.3.4 Breakup description 1973-79

3.3.4.1 Breakup 1973

Breakup information for the spring of 1973 is available through satellite imagery, AES ice charts, and the field survey report by Memorial University.

The first signs of breakup were apparent in early May. Two large cracks were observed on May 16 (by the field party from Memorial University) to extend across the lake off Adams Point and between Eskimo Paps and Lowland Point. Satellite imagery showed open water in Goose Bay and The Bight on May 26. Many large cracks and patches of open water existed east of Epinette Peninsula. Even though the west end of the lake was mainly open water, the ice in the east end was still very thick. Ice thickness measurements made on May 27 between Eskimo Island and Gull Island (by the MACDONALD icebreaker probe) ranged between 1.1 and 2.2 metres, while the ridged areas had thicknesses in excess of 4 metres.

The ice charts produced by Environment Canada show 6/10 ice concentration from Lowland Point to St. John Island and 2/10 concentration east of this area on June 11. By June 15, the lake was practically ice-free with only one patch of ice remaining in the vicinity of Etagaulet Bay.

3.3.4.2 Breakup 1974

Cracks between Epinette Point and North West River, Long Point to Julia Point, and from Lowland Point to the middle of the lake were

reported on May 25, 1974 by a field party from Memorial University. A large portion of the lake was open water by June 7 (Figure 3.11) while a landfast section still existed between Eskimo Island and Gull Island. By June 14, the ice charts indicated a 2/10 coverage over the southeast portion of the lake.

3.3.4.3 Breakup 1975

The ice charts show that open water first appeared east of St. John Island. On June 2 and 9, there was open water at both ends of the lake with 10/10 ice coverage between. By June 16, the lake was completely ice free.

3.3.4.4 Breakup 1976

During spring 1976 the process of breakup took a considerably longer time than the previous year. Patches of open water first appeared between Neveisik Island and the Narrows on May 7. On May 28, a large section of 8/10 coverage still remained in the middle of the lake. By May 31 the lake was open for navigation purposes, although a large patch of ice still remained along the south side of the lake.

3.3.4.5 Breakup 1977

The first signs of breakup in 1977 occurred on May 19 with open water appearing east of Neveisik Island. By June 2, the lake was ice-free except for a patch with 2/10 concentration east of the Epinette Peninsula.

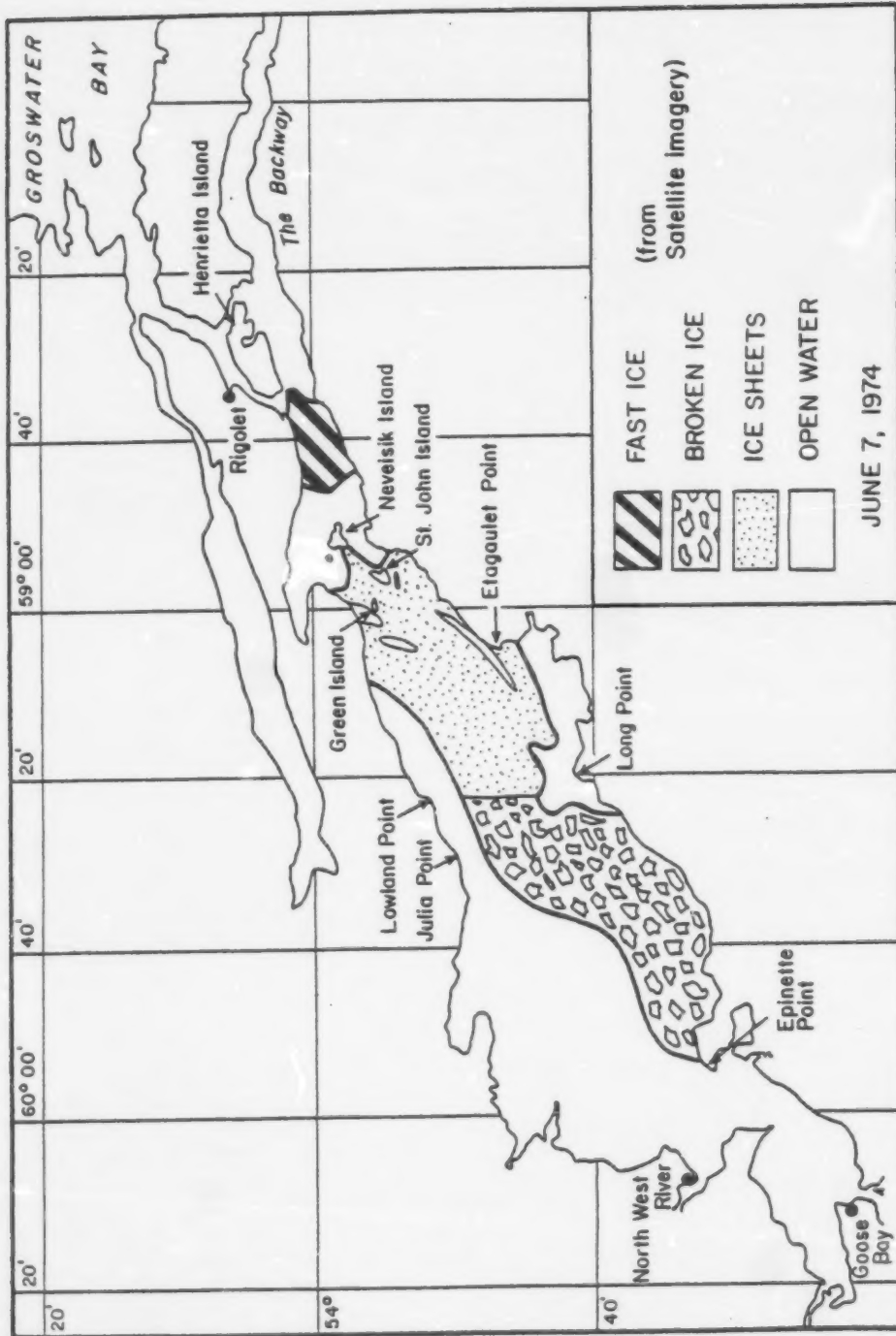


FIGURE 3.11 SKETCH OF BREAK-UP ICE CONDITIONS

3.3.4.6 Breakup 1978

The ice charts indicate that the first signs of major deterioration occurred on May 21, 1978. By June 11, the lake was totally ice-free.

3.3.4.7 Breakup 1979

During Spring 1979, open water first appeared on May 10 at the mouth of the Northwest and Kenamu Rivers. The western half of the lake was ice-free on May 21. There was 7/10 ice concentration between Long Point and Green Island. The area east of this had a concentration of 1/10. By May 27, the lake was completely ice-free. This was the earliest date of complete breakup for the seven years studied.

3.4 Pack Ice

3.4.1 General Description

In an average year, pack ice exists in some parts of the study area from mid-December to mid-July and usually covers the entire study area in varying concentration from late December to late June. The pack ice consists of locally formed first-year ice and varying amounts of first year and multi-year Arctic ice. The content and distribution of ice type in the pack are quite variable.

Two exceptional seasons with regard to weather conditions, 1960 and 1973, have demonstrated the opposite extremes in ice coverage in the Labrador Sea. The winter of 1973 was one of the coldest on record in Newfoundland. The waters of the Labrador current were abnormally cold,

chiefly because the Arctic summer of 1972 was particularly cool. Close pack ice extended to the eastern edge of the Grand Banks as far as 45°W longitude and 44°N latitude. In contrast, the winter of 1960 was one of the warmest on record and the ice field did not extend beyond Cape Freels. In more normal years the pack ice extends to the eastern edge of the Grand Banks, sometimes to the Flemish Pass, and generally not too much further south than 46°N. Some early ice observations as reported by C-CORE (1978) indicate that conditions may have been much more severe. Reports from the 1800's tell of ships finding ice four hundred miles off the Labrador Coast in July. In 1816, the Labrador Coast was apparently blocked with ice for the entire year, while in 1880, the drift ice bordered the Labrador Coast for about 65 km during the middle of July. It is difficult to assess the validity of these records; however, they must be viewed as indicating that more severe ice conditions than experienced in recent years may occur.

3.4.2 First-Year Ice

First-year ice can form as shorefast ice or open sea ice which would generally reach a thickness of approximately 1 m by the end of the season if no deformation occurred. More typically, constant wave and wind action causes ridging and rafting of the ice into packs with variable topography and subsurface profile. Shorefast ice extends 10 to 12 km from the coast and is often separated from the pack by a distinct rubble line. During periods of offshore winds, a lead may exist between the shorefast and pack ice zones.

By the end of December, the ice edge is usually about 75 km east of Groswater Bay although the maximum extent, based on the study of AES Ice Charts for 1969-79, may be as much as 225 km. From a consideration of concentration and extent of coverage, the pack usually reaches its peak during March, after which it increases its areal extent by drift to the south and southeast while its mean concentration decreases. The mean monthly concentrations as determined from the ice charts are shown in Figure 3.12. By the middle of May, large areas of open water are found within the pack, and strings and tongues of ice detached from the main pack are usually found around the periphery. By the end of May, open water normally exists along the coast from Groswater Bay to the Strait of Belle Isle, extending 10 to 20 kilometers from shore. For this month, in a light ice year, there may be no ice of 6/10 or greater concentration found south of 55°N (Cape Harrison). (As discussed in Section 6.2, concentrations of 6/10 or more constitute essentially the total resistance to ship movement in ice.) On the average though, 6/10 or greater ice concentration may be encountered up to 140 kilometres east of Groswater Bay and may spread down to the Strait of Belle Isle. Six tenths or greater concentration might be encountered to a maximum of 335 kilometers east of Groswater Bay and south to a point 350 kilometres east of St. John's.

From an analysis of SAR and SLAR imagery for February and March 1977-79, it would appear that leads within the Labrador pack are randomly oriented and frequently occur within areas containing floes of diameters 20 to 2000 metres. They tend to occur near the coast. The dimensions

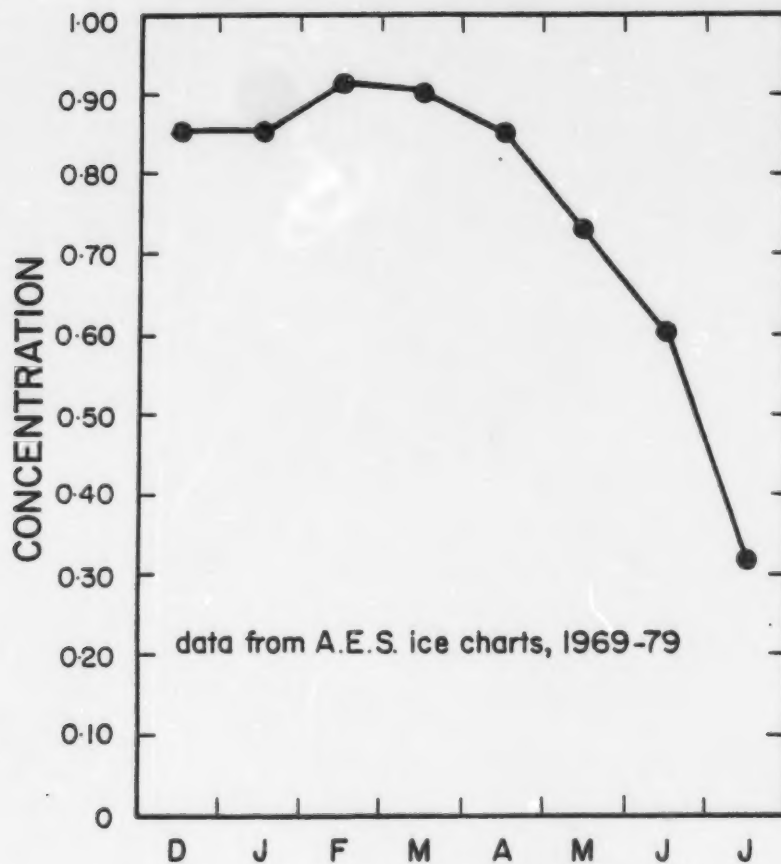


FIGURE 3.12 PACK ICE CONCENTRATION
ALONG A LINE OFF GROSWATER BAY TO 52°W

of the leads are generally in the order of a few kilometres except for flaw leads between shorefast ice and the pack which may extend a considerable distance along the coast even in mid winter during periods of offshore winds.

From a limited number of satellite images of the study area during mid-winter 1974 to 1979, it was seen that Groswater Bay remains largely free of heavy pack ice and was shown as completely open except for some landfast ice on a number of images. Landfast ice sometimes covers the western end of the bay in the area east of The Narrows which, along with Pike Run, was essentially ice free in all cases. Unlike the SAR and SLAR imagery referred to above, the satellite photos showed parallel leads extending from the shorefast ice through the pack in a direction essentially perpendicular to the coast as the ice crossed the outer reaches of Groswater Bay. A ship approaching Groswater Bay from approximately a northeast direction could use these leads to facilitate movement through the pack. These leads which were often separated by large expanses of ice may have been missed on the SAR and SLAR passes either because of their nonexistence during these overflights or because of the relatively narrow track covered by the sensors.

The pack is subjected to the dynamic influences of swell, wind, and the Labrador current. These ensure that there is always relative motion within the pack. As a consequence, continuous smooth ice is not a normal feature of Labrador Sea pack ice. There is considerable roughness in the form of rafting, ridging and hummocking and floe sizes tend to be small as the result of collision and abrasion of the ice.

Figures for average floe size in the Labrador Sea vary according to several sources. Imperial Oil Limited (1977) reports an average floe size of 10 m maximum dimension with few floes greater than 30 m. Nolte (1971) notes an average floe size of 20 m with floes up to 90 m observed. Average floe sizes of 30 m were obtained by NORDCO personnel during February, 1977 at the landfast ice boundary and these reduced to 15 m ten kilometres seaward into the pack. An analysis of the SAR and SLAR imagery referred to above for February 1977 revealed that 50 to 60 percent of the ice up to 300 kilometres east of Groswater Bay consisted of 20 to 500 metre floes of first year ice. In February 1979 along the same route approximately 90 percent of the pack consisted of 20 to 500 m floes. In general, it was found that floes greater than 20 m in diameter occurred near the shore as opposed to the outer edge of the pack. The decrease in the size of floes from the coast to the outer edge of the pack can be attributed to the greater influence there of waves and swell.

From thermodynamic considerations, it is estimated that undeformed first-year ice could attain a thickness of 1 m to 1.5 m depending on the origin of the ice. An average thickness of 1.2 m of consolidated first year ice has been calculated from floe data collected in February, 1977 by NORDCO Limited (NORDCO, 1977). Nolte (1971) obtained thicknesses in the range 0.3-1.23 m during March. Bradford (1973) reports an average thickness greater than 1.5 m obtained from measurements south of Groswater Bay near Spotted Island. Imperial Oil Limited (1977) cited an average measured thickness of 1 m for first-year floes in Davis Strait. Thicknesses

of rougher ice are generally considerably higher than these values. Average thicknesses of 3 to 5 m in rafted and ridged ice are reported by Bursey (1977). According to Nolte's survey (1971), pressure ridges were frequently encountered and averaged 3 m in thickness, 3 to 4.5 m across and 9 to 15 m long. An estimated maximum thickness of 7.5 m was observed. The SAR and SLAR analysis for February, 1977 mentioned above, found ridges to be spaced 1-3 km apart near the entrance to Groswater Bay. A ridge sail height of less than 2 m was estimated which would imply an average total thickness of approximately 10-12 m.

3.4.3 Multi-Year Ice

Multi-year ice (including second-year ice) in the Labrador Sea results from ice that has survived at least one summer's melt further north. Because it is usually considerably thicker, stronger and harder than first-year ice, it is considered to pose a significant hazard to navigation in the study area. There is very little information on the concentration of multi-year ice in the Labrador pack, but it has been estimated to be between 1 and 10 percent of the total pack for May in a typical year (Fisheries & Environment Canada, 1978).

In the present study, the ratio of multi-year ice to total ice was obtained from the AES ice charts for 1969-79 and the monthly averages calculated. According to the results as shown in Figure 3.13, June experiences the highest percentage of multi-year ice. According to the ice charts, multi-year ice is more often evident along the coast than towards the outside of the pack. The only known published measurement

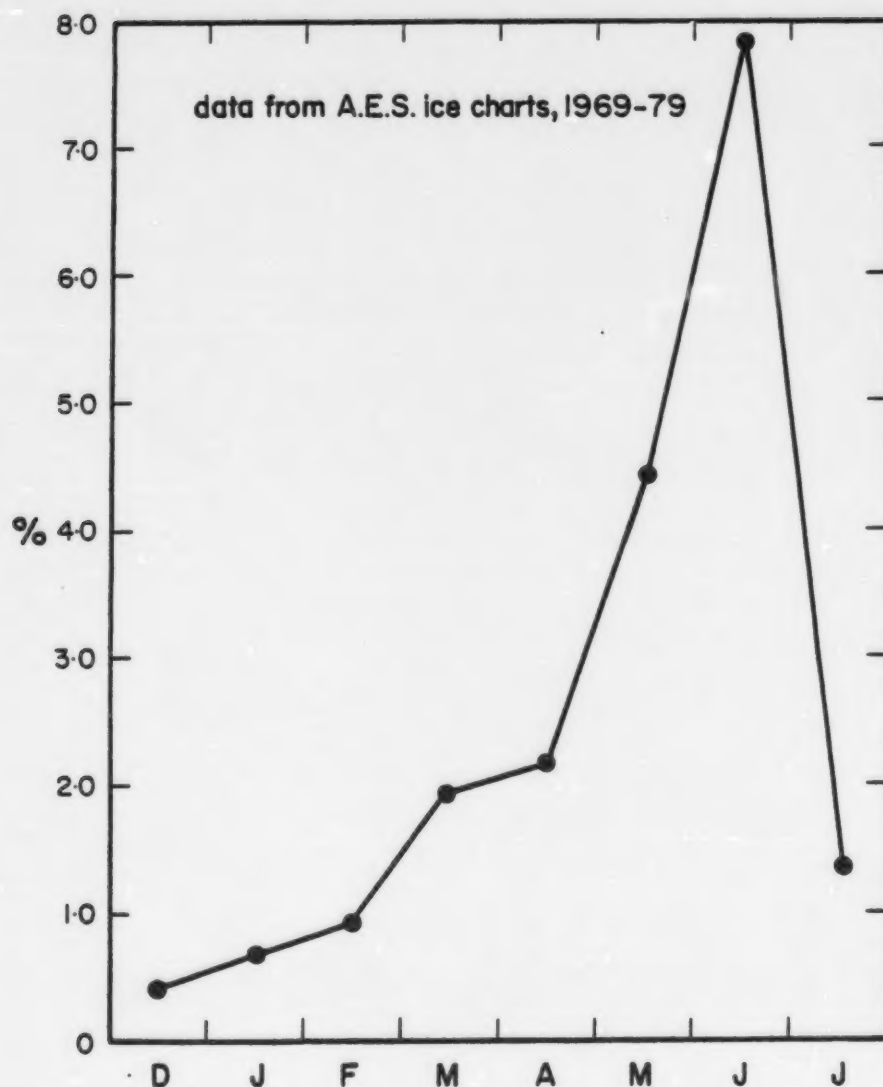


FIGURE 3.13 PERCENTAGE OF MULTIYEAR ICE
WITHIN PACK ICE OFF GROSWATER BAY

of the thickness of multi-year ice in the study area is that by C-CORE in June 1978. The calculated thickness from an impulse radar echo from a floe in Groswater Bay was 14.6 m (Rossiter et al 1979). Measurements of multi-year floes in the Davis Strait indicate that thicknesses up to 16 m may occur with floe sizes ranging up to 100 m in diameter (Imperial Oil Limited, 1977).

3.5 Storms

A review of climatological studies was carried out in order to determine the storm characteristics in the study area. While a number of such studies have been conducted (Archibald, 1969; Klein, 1977; Reitan, 1977), essentially two studies by Bursey et al (1977) and Merserve (1974) are appropriate for present purposes. Bursey et al., examined data for the years 1899-1903 and 1916-1920 and derived the tracks and frequencies of storms (cyclones) which affect eastern Canada during January, April, July and October. Merserve used data from 1965-74 to derive primary and secondary tracks and the number of cyclones present in 10-degree square geographical areas. Although these studies apply to very large areas, it is possible to obtain an estimate of the number of storms affecting the study area during different times of the year. Figure 3.14 shows monthly estimates of the number of storms in the study area based on nine years of data. These estimates represent about 30 to 40 per cent of the total number of low pressure disturbances in all of eastern Canada.

Of the two major cyclone paths which have been identified by Bursey

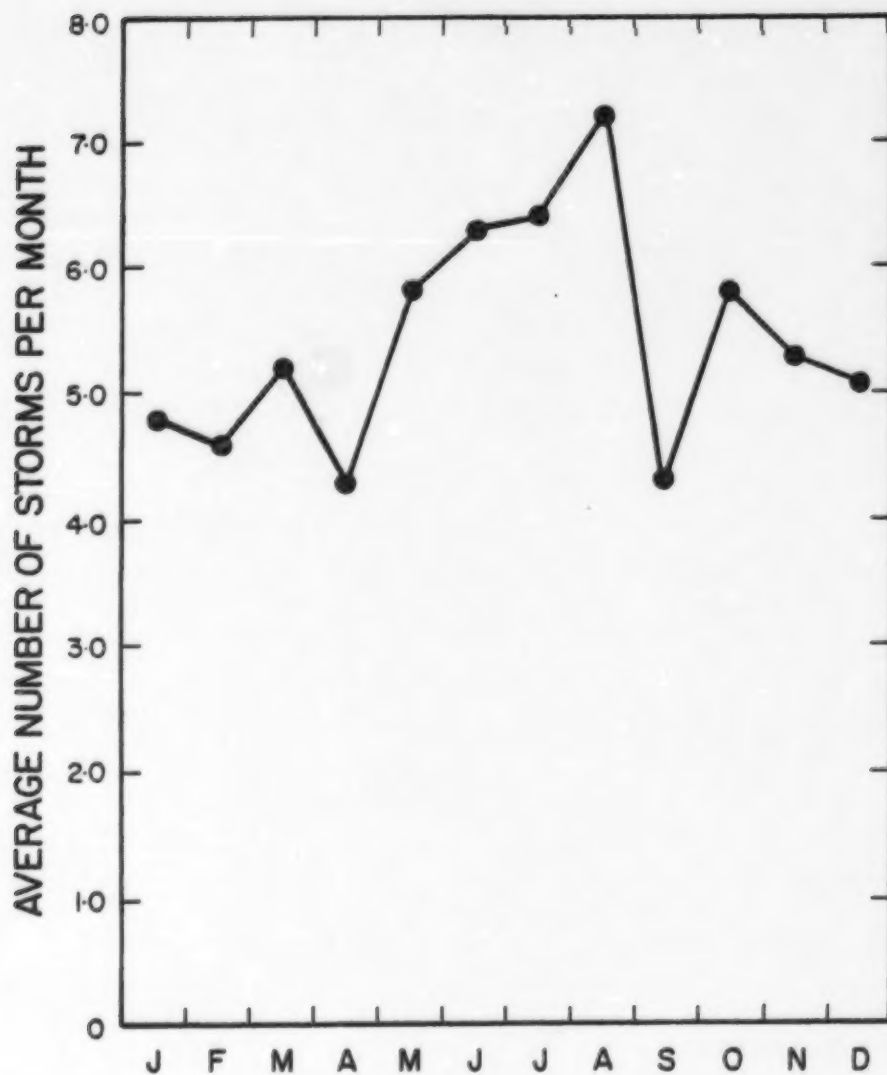


FIGURE 3.14 AVERAGE NUMBER OF STORMS PER MONTH

and Merserve as affecting the study area, the path which passes to the south of the area will result in more intense storms during fall and early winter. These storms often recurve into the Labrador Sea after passing the island of Newfoundland. Very heavy snowfall associated with southeasterly storm force winds can occur ahead of such low pressure disturbances followed by stronger westerly winds and low temperatures. Freezing spray often accompanies such storms. Northeasterly winds may sometimes occur during these disturbances and create very poor fog conditions in Groswater Bay and possibly in Lake Melville as well.

Cyclones which pass along the northern track over Lake Melville from the west will be less intense on the average than storms following the southern track. Gale force winds and light snowfall or rain are associated with such storms.

3.6 Winds

In order to obtain information on extreme winds in the study area, data from ship reports and ocean weathership (OWS) BRAVO (56.5°N, 51°W) for periods of 28 and 24 years respectively were investigated. While BRAVO is not in the study area, it is a rather reliable source for general wind information since it would have maintained location in extreme weather conditions. Ship reports are, however, subject to fair-weather bias, and this is usually reflected in a trend to lower average values of weather data than would have actually occurred in the area. Data from BRAVO tend to offset this tendency. However, because BRAVO was located a considerable distance offshore, winds recorded there would

not have been influenced by the Labrador land mass to the same extent that observations in the study area would be affected, especially as ships approach the coast. For that reason mean winds at the BRAVO location would generally be somewhat higher than in the study area.

For the purposes of this study, only wind speeds greater than 70 km/hr (40 kts) have been considered. Further consideration is given to onshore winds of lower speeds in Section 3.7. From an analysis of ship reports, it was found that wind speeds exceeding this value in the study area occur only two to three per cent of the time in winter and drop to 0.5 per cent during summer. The greatest exceedence of this value occurred in November when 3.9 per cent of the wind speeds were greater than 70 km/hr. This reflects the fact that a major storm track covers the study area during November and more intense storms and higher winds can be expected to occur. From an analysis of weathership BRAVO data, it was found that wind speeds exceeding 70 km/hr occurred a maximum of 7.6 per cent in January and dropped to 0.2 per cent in July and August.

While these statistics indicate that wind speeds of 70 km/hr are not often exceeded, there have been reports of some severe winds in the study area. Table 3.2 contains such monthly extreme winds as obtained from ship reports and OWS BRAVO.

Wind direction is predominantly northwest except during summer when southerly and southwesterly winds are most frequent. The frequency of northwest winds is highest during December at 27 percent.

TABLE 3.2
Extreme Monthly Winds

	<u>Ships</u>		<u>BRAVO</u>	
	km/hr	kts	km/hr	kts
January	29	56	128	70
February	130	74	128	70
March	128	73	109	62
April	92	52	106	60
May	113	64	106	60
June	92	52	92	52
July	88	50	99	56
August	141	80	84	48
September	102	58	107	61
October	128	73	113	64
November	123	70	111	63
December	128	73	120	68

It is not expected that winds in general will have a significant effect on the performance of ships on the open ocean except to possibly induce greater icing risks. Once the ship is within the pack ice, however, its performance may be very susceptible to wind conditions, and this matter is discussed in Section 3.7.

3.7 Sea Ice Pressure

3.7.1 Introduction

A vessel operating in pack ice conditions is susceptible to pressure influences created by wind and water stress on the ice. Depending on the displacement and power of the vessel, such sea ice pressure could result in considerable delay during the transit through the pack. In this section of the report, consideration is given to the ice pressure phenomenon and a review of previous investigations is made. Unfortunately, little information is available on the magnitude of this problem in the study area primarily because of the limited navigation season. However, studies in other areas are of some relevance and some extrapolations may be made.

3.7.2 Previous Studies

The only available studies of the relationship between winds and sea ice pressure generation have been carried out in the Gulf of St. Lawrence and Baffin Bay (Bradford, 1971, 1972). In the former study, a search was made of the bridge logs of the Canadian Coast Guard ice-breakers LABRADOR and JOHN A. MACDONALD for references to merchant ships beset in ice pressure situations. Data were extracted only if two

criteria were met; viz., it was stated in the logs that ice was under pressure and it was stated that a particular vessel was actually beset. The search was restricted to the Gulf of St. Lawrence - Sydney Bight area between 1961 and 1969 inclusive, during which time a total of 124 merchant ships were reported beset in ice pressures on 100 separate occasions. The relative power of the ships reported beset was calculated in an attempt to relate ice pressure severity with ship performance. Relative power for each vessel was calculated by dividing shaft horsepower by loaded waterline length. Length rather than displacement was used on the assumption that friction of ice on the hull would be a critical factor in slowing ships under ice pressure.

It was found that ice pressures hindering merchant shipping in the Gulf of St. Lawrence were most frequent within 20 nautical miles of shore in ice concentrations of 9/10 or more, of which 5/10 were grey-white (16-30 cm thick) or older. While incidents of ships being beset with horsepower to length ratios of up to 20 to 1 were reported, ships with ratios of 10 to 1 and less were reported to be beset much more frequently. Pressures occurred most often in periods of onshore winds, and once generated apparently became more intense with proximity to shore. It is suggested that, given the winds and horsepower to length ratio, it is possible to calculate the distance the vessel should remain offshore in order to avoid pressure problems.

Ice pressure during periods of offshore winds often seemed to be related to major shifts in wind direction, especially when speeds near

the shift time were of the order of 40 km/hr (Force 6). The pressures encountered appeared to be less severe than those occurring during onshore winds. The ships with the larger power to length ratios did not become beset even though offshore winds tended to be stronger than onshore winds.

In the Baffin Bay study, sea ice pressures encountered by the icebreaker LOUIS ST. LAURENT while escorting the tanker MANHATTAN in the Baffin Bay area in April to May 1970 were observed along with certain wind, ice and ship performance data. A qualitative rating based on the behaviour of the ice in MANHATTAN's track was used to estimate ice pressure severity according to the following:

<u>Pressure rating</u>	<u>Identification</u>
Light	MANHATTAN's track closes <30% within 1 mile
Medium	MANHATTAN's track closes 30-80% within 1 mile
Heavy	MANHATTAN's track closes 80-99% within 1 mile
Severe	MANHATTAN's track closes completely within 1 mile, ridges forming along track, ST. LAURENT unable to manoeuver at full power

Pressure was observed in the ice on 19 of the 42 days spent in ice conditions with a total of 31 pressure episodes being observed. It was found that ice pressure frequency increased with wind speed and that the chance of encountering ice pressure appeared to be about twice as great for wind speeds of 37 km/hr (20 kts) to 55 km/hr (30 kts) as for speeds less than 18 km/hr (10 kts). The severity of the pressure increased

with wind speed. Heavy or severe pressures were noted on only four of thirteen pressure days when winds averaged less than 37 km/hr (20 kts) but were observed on all six pressure days when winds averaged greater than 37 km/hr (20 kts).

It was found that major wind shifts seemed to generate ice pressure and this, as is noted, is not unexpected since abrupt wind shifts are often observed with the passage of deep atmospheric low pressure systems which would very likely cause convergence of the pack. Eighty per cent of these shifts of 80 degrees or more were accompanied by pressure episodes, some of which were the heaviest encountered. It is noted that this pressure was usually observed within one hour of the wind shift, and in heavier winds the pressure seemed to occur simultaneously with the shift.

It was determined that 84 per cent of the pressure situations occurred when winds were classed as onshore, and the pressure generation during offshore winds was primarily attributed to a major wind shift. It is noted that the effect of ice thickness was difficult to assess. While the average ice thickness observed when heavy ice pressure occurred was thicker than when medium and light pressures were noted (0.95 cm as compared to 0.86 cm) one of the heaviest episodes occurred when the ice was less than 0.50 m thick. In all cases of pressure, the ice coverage was estimated to be 9/10 or greater.

In terms of ship performance, it is noted that the ships averaged 69 km (37 nautical miles) on days when ice pressure was not observed and

57 km (31 miles) when pressure was observed, the daily distance being determined for the time between 0800 and 2000 hours. Considering that pressure was observed on only half of the travelling days, this suggests that the occurrence of ice pressure increased the elapsed time of the voyage by eight per cent. This calculation does not include four days (nine per cent of the total time) during which the ships did not move after being jammed in one severe pressure episode. Therefore, the total loss rate due to pressure effects was 17 percent.

As in the Gulf of St. Lawrence study, the data indicated an increase in pressure severity with proximity to shore. The average distance from shore at which light, medium and heavy pressures occurred was 89, 72 and 59 km respectively. While light pressure did not noticeably retard the ship's progress, both medium and heavy pressures stopped the ST. LAURENT on several occasions when only intermediate horsepowers were available. The vessel became beset in severe pressure on only three occasions when operating within 20 per cent of its maximum horsepower. It is concluded from this experience that ships with the navigation capability of the ST. LAURENT with a horsepower to length ratio of 65.5 could expect to encounter ice pressures approximately 50 per cent of the time when operating in late winter in Baffin Bay pack ice. The overall effect of the pressure would be to increase transit times but probably by not more than 20 per cent. The risk of becoming beset would occur whenever ships approached within 46 km (25 nautical miles) of shore in onshore winds of over 37 km/hr (20 kts).

3.7.3 Considerations of ice pressure in the study area

While there are no known studies on the relationship between sea ice pressure and environmental factors and ship parameters in the study area, it is possible to carry out some extrapolations of the above-mentioned results. This, of course, must be done with some caution since the studies described have, in themselves, been based on a limited number of observations, and conditions in the present study area can be considerably different from the Gulf of St. Lawrence and Baffin Bay.

In the first instance, the prevailing winds in the study area are from the land to the sea, while in Baffin Bay and the Gulf of St. Lawrence, winds from a number of directions could be classed as onshore because these areas are, to a large degree, surrounded by land masses. Navigation in near shore water would benefit from offshore winds in the study area since the waters become calmer, the ice pack moves further offshore and leads are created near the shore. The highest incidence of onshore winds of all speeds occurs from April to June which coincides with the ice breakup period. Instead of the wind accelerating the breakup by driving the ice offshore, it works to slightly inhibit breakup and interfere with navigation by blowing onshore about 37% of the time (Bradford, 1973).

While the study area may experience a smaller incidence of onshore winds than Baffin Bay and the Gulf of St. Lawrence, often these winds are associated with intense storms which turn northwestward after passing the Island of Newfoundland from an initial northeastward track.

(Storm tracks have been discussed in Section 3.5.) Wind speeds are generally higher in the Labrador Sea due to the presence of the open water which creates a vertically unstable atmospheric situation. The more energetic wind patterns aloft are transmitted to the surface and result in high onshore winds as compared to other areas.

In order to determine the frequency of onshore winds in the study area, wind data were obtained from SSMD (Summary of Surface Meteorological Observations) data. The frequency of occurrences of onshore winds greater than 37 km/hr (20 kts) and 56 km/hr (30 kts) are shown in Figure 3.15. Assuming that such winds would cause pressure problems for a ship when the ice is sufficiently concentrated, pressure problems could be experienced about 12.5 percent of the time in January and with lower frequency during other months. It should be remembered, however, that the ice will be thicker in February and March and pressure severity is a function of thickness; hence any pressure occurrence during these months would be more severe than earlier in the winter. Until more data are available from the area on actual incidents of ships being beset, it is clearly not possible to specify with any degree of confidence the extent of delays that would be encountered during year-round navigation. It is expected, however, that pressure problems will be less severe here than further north for example in Baffin Bay which is more susceptible to winds from various directions and which contains thicker ice. Given that delays in Baffin Bay due to pressure could be expected about 20 percent of the time, and that the frequency of onshore winds in the study area are as described above, it is perhaps not unrealistic to

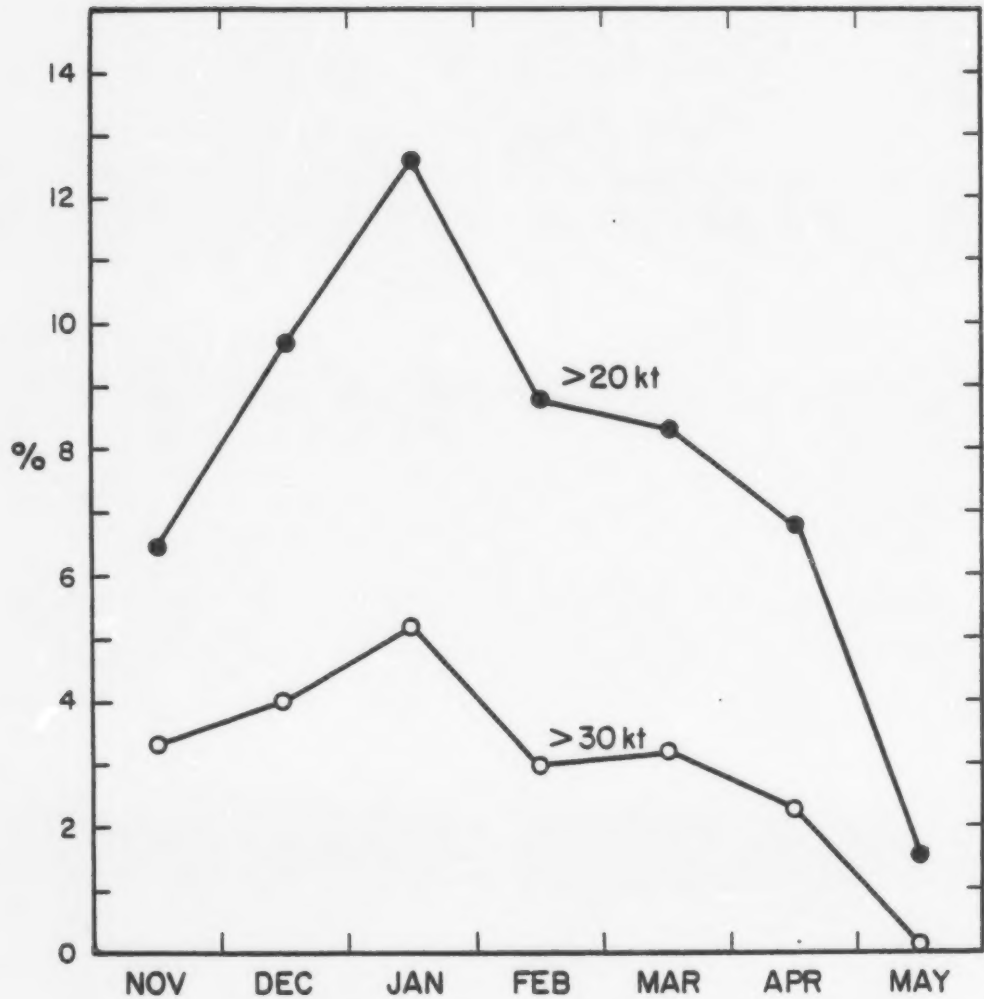


FIGURE 3.15 PERCENTAGE FREQUENCY OF ONSHORE WINDS
(N.E. THROUGH S.E.) EXCEEDING 20 & 30 KNOTS

assume that delays due to wind induced pressure in the study area for a ship capable of efficiently negotiating in the pack would be in the order of 10 to 15 percent.

A major complicating factor in attempting to predict the incidence of ice pressure generation and its severity in the study area is the Labrador current. The effect of this current could be to produce pressure even when winds are offshore if the southward-drifting ice becomes compressed by eddies and gyres in the current (Bradford, 1979) and to compound pressure problems when winds are onshore. Bradford notes that this problem is evident in the Gulf of St. Lawrence when ships approach the Gaspé Peninsula from the east and come under the influence of a southerly flowing current along the Gaspé coast. While it is difficult to predict how the effects of current would increase the delay in ship transit through the pack, it is likely that, when coupled with the wind effects, the overall result will be to increase the delay to more than the 10 to 15 percent suggested above.

3.8 Reduced Visibility

While the use of radar clearly reduces the susceptibility of ships to conditions of poor visibility, it is expected that during certain periods conditions will be such that, as a matter of caution, the vessel's speed will be reduced. This will be especially so in the case of navigating among ice forms which may result in dubious images on the radar screen. As mentioned elsewhere in this report, icebergs may be undetected due to the manner in which the radar beam interacts with the

ice surface and often growler images may be obliterated due to sea surface reflection especially in heavy seas. It would be somewhat risky to proceed at cruising speed in such ice conditions particularly if visibility is reduced.

To ascertain the frequency of occurrence of reduced visibility, it is considered that visibilities should be at least one-half the stopping distance of the ship at any given time. In dangerous ice conditions, this restriction would probably be more severe. For the purposes of this study, visibilities of less than 0.9 km (0.5 nautical miles) are assumed to be necessary for safe navigation.

Reduced visibility can result from the formation of fog near the water surface or from low ceiling and precipitation (especially snow) during inclement weather. In Figure 3.16 the frequencies of visibilities of 0.5 n.m. for various portions of the study area are presented. Reports from Weathership BRAVO are used to represent the far offshore, SSMO reports are used for the area covered by the pack ice, and Hopedale and Cartwright data are considered for conditions along the coast and in Groswater Bay. Goose Bay data are also included; however, no reports of visibilities less than 0.9 km (0.5 n.m.) were found, and therefore visibilities of 1.9 km (1 n.m.) have been considered. As is evident from the graphs, visibilities improve with proximity to shore. For the period December to May, visibilities of less than 0.9 km will be encountered on the average 10 percent of the time in or near the pack while 15 to 20 percent is typical of the ocean outside the pack. Along

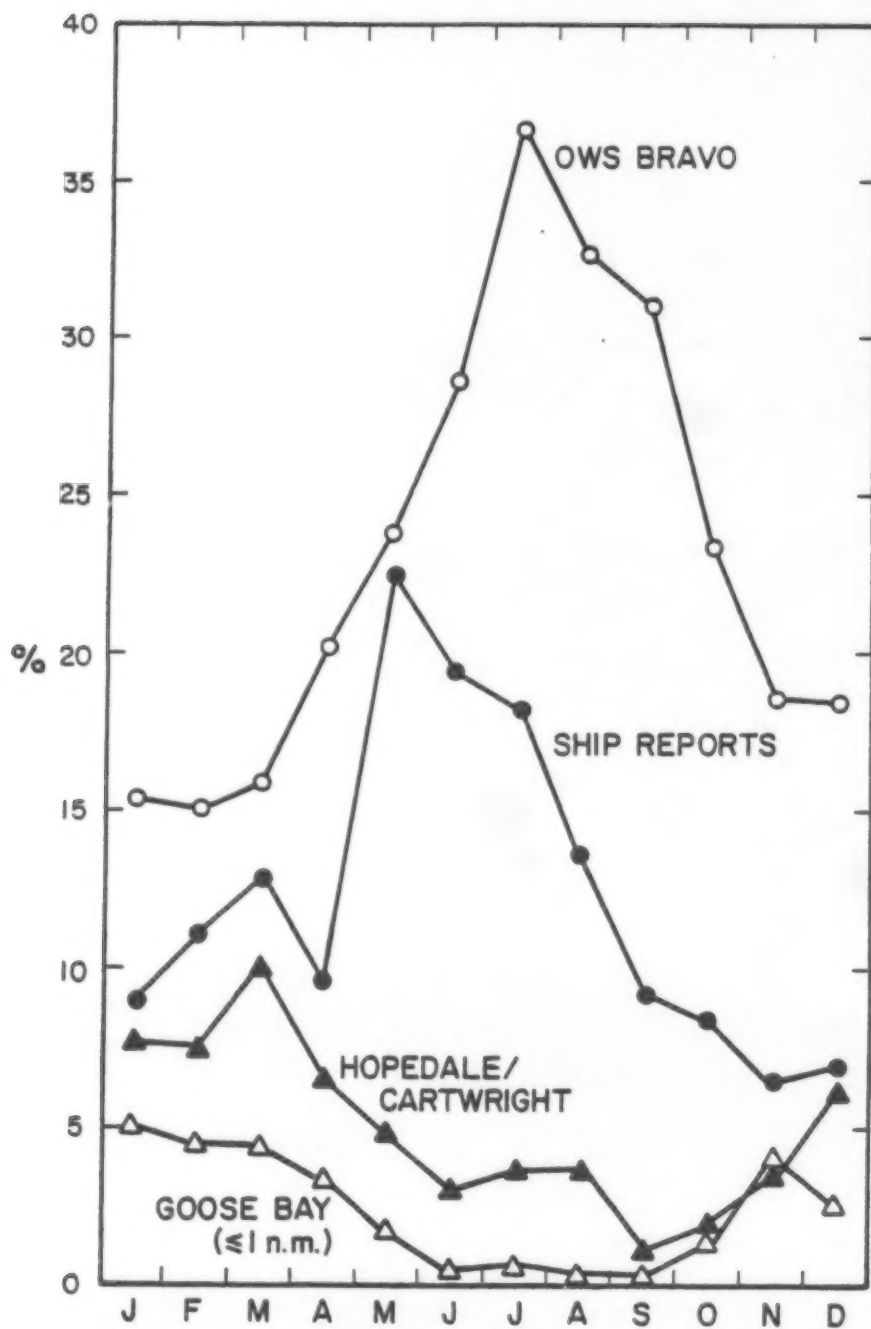


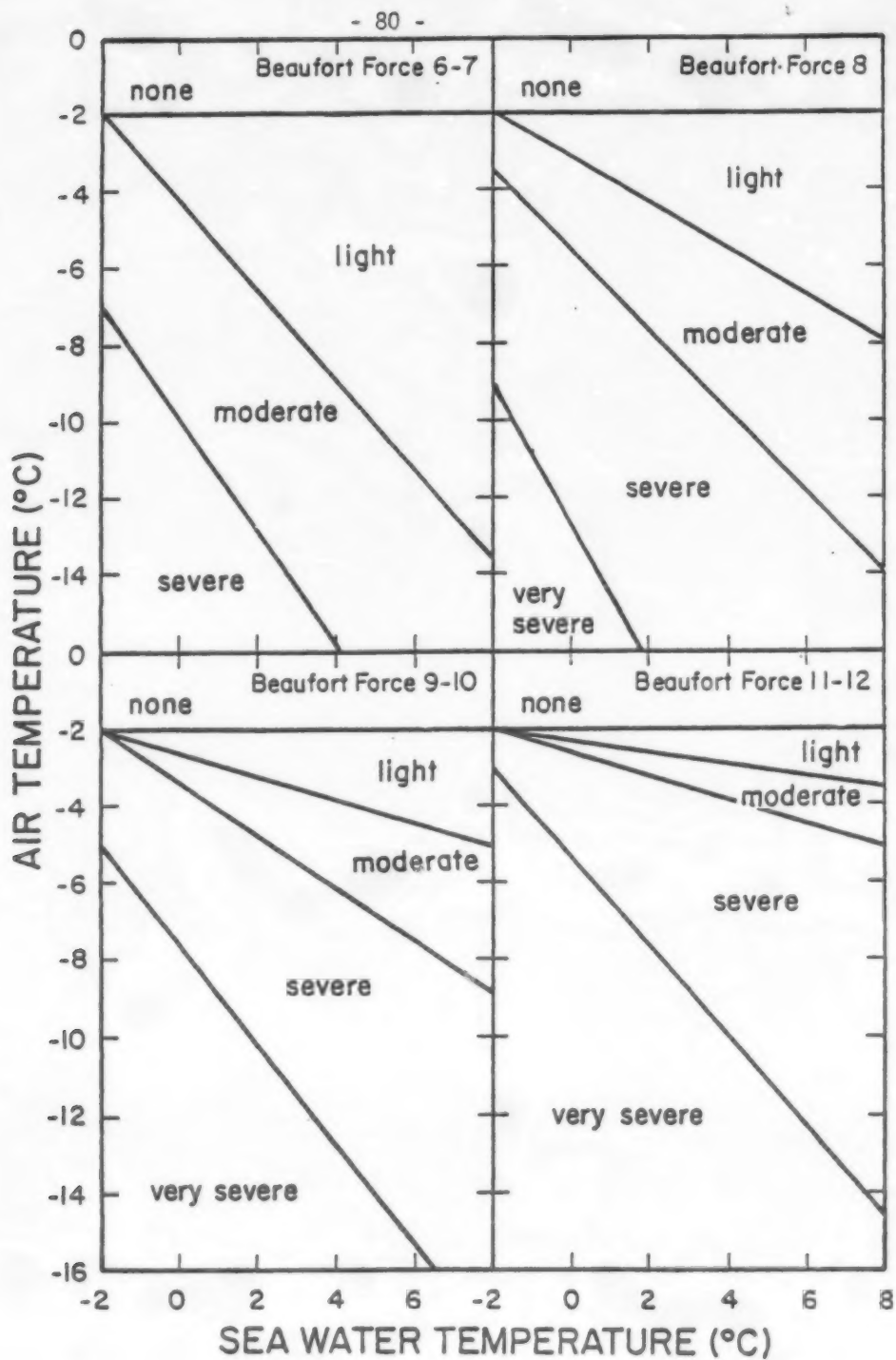
FIGURE 3.16 PERCENTAGE FREQUENCY OF VISIBILITIES OF 0.5 NAUTICAL MILES OR LESS

the coast and in Lake Melville, reduced visibilities will occur 5 to 10 percent of the time.

3.9 Icing

In the open sea, ice accretions from freezing spray can become a serious problem for ships. The icing potential exists when the temperature falls below the freezing temperature of sea water (usually about -2°C) with wind speeds equal to or greater than 37 km/hr (20 kts). The severity of icing depends on the combination of low temperature and high wind speed, common in the study area from late November to the end of April. The effect of ice accretion on a vessel is to increase the top-weight of the ship and effectively raise the centre of gravity so that the stability is reduced.

The dependence of icing rate on wind and air temperature is shown in Figure 3.17. These rates are based on data collected by Mertins (1968) from approximately 400 observations from fishing trawlers and German research vessels. The occurrence of icing in an area off Groswater Bay bounded by 52.5°N and 57.5°N and 52.5°W and 57.5°W is shown in Figure 3.18. These data have been obtained from ship reports for the years 1946 to 1973 inclusive. While the number of icing occurrences is largest in January, the most severe icing accumulation occurs in February. This increase is associated with the shift of the Icelandic low eastward bringing stormier weather into the area. A portion of the area for which the data were extracted is outside the pack ice zone and the icing rates are probably more applicable to that smaller area. It is clear



DEGREE OF ICING (cm/24 h) – light = 1-3, moderate = 4-6
 severe = 7-14, very severe ≥ 15

FIGURE 3.17 ICING DIAGRAM FOR FISHING VESSELS

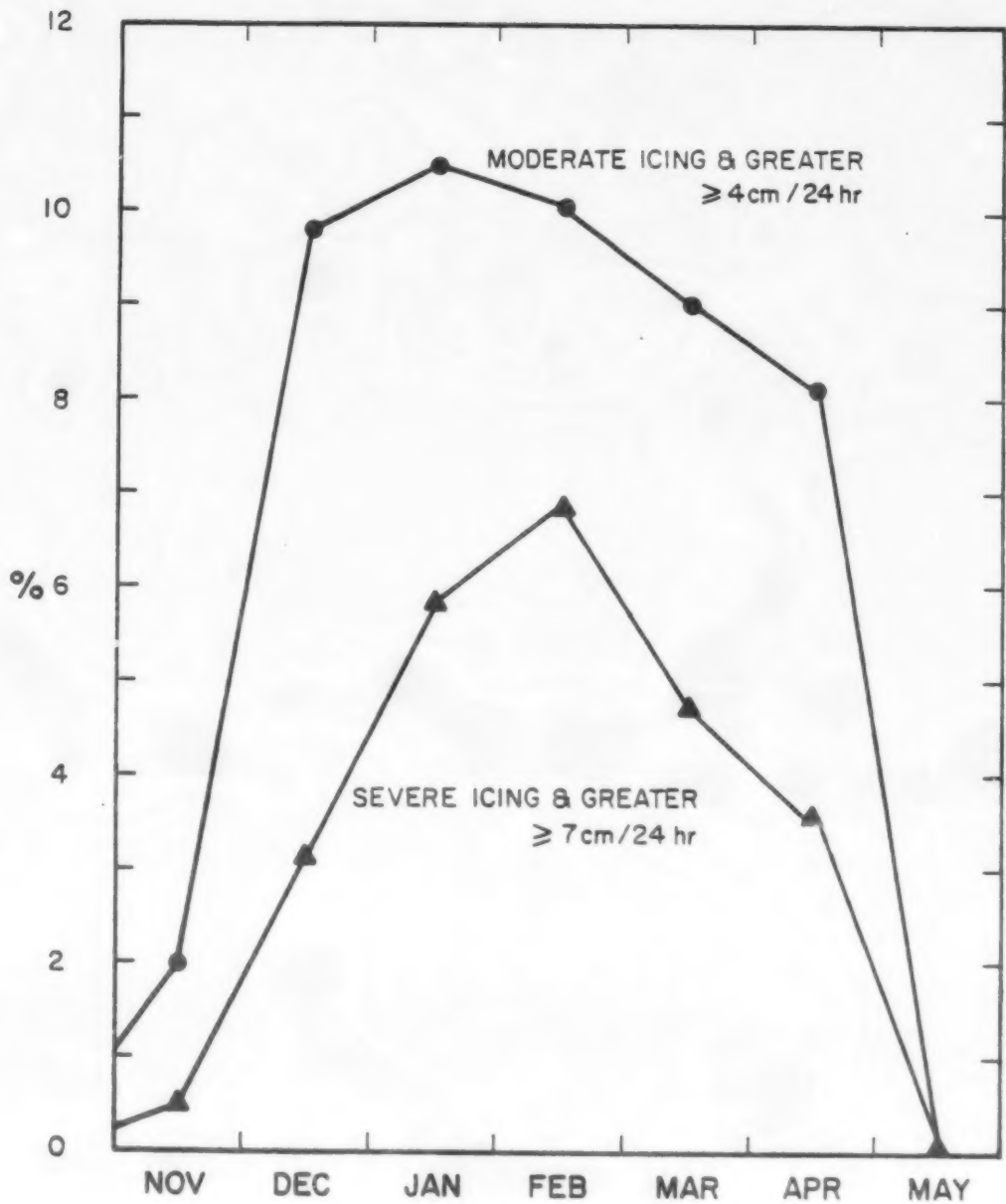


FIGURE 3.18 PERCENTAGE FREQUENCY OF ICING
FROM SEA SPRAY FOR AREA 52.5-57.5N, 52.5-57.5W

that icing will generally not be a problem in the pack unless the wind is blowing along a lead of some considerable area, and, in fact, entering the ice is usually the easiest way to avoid icing problems.

The effect of icing on a vessel is clearly dependent on vessel size and is mostly experienced in relatively small cargo ships and fishing vessels. While there have been some reports from the Baltic and Kara Seas of larger ships having problems with icing, in general it is limited to vessels of a few thousand tons. Although icing could lead to a hazardous situation given the right combination of environmental conditions, and precautions should be taken to avoid it, in general, it is not expected that icing will cause significant delays for the types of ships capable of operating year-round in the study area.

3.10 Icebergs

The dangers of icebergs to shipping in the study area are legend, and clearly due caution is required when navigating in iceberg-frequented waters. This is especially true since, as is mentioned elsewhere in this report, icebergs may not be evident on the radar screen if the sides of the berg do not allow the desired reflection to occur. Growlers may cause added problems in that they have low freeboard and may be disguised by reflections from the sea especially in the case of high waves.

While the greatest danger from bergs is during early summer when the berg density is at its peak and a large amount of open water exists

in the study area, bergs may still cause problems in winter especially at the edge of the pack which is often shown as bergy water on the AES Ice Central Charts.

In order to determine the frequency of bergs at various times of the year in the study area, the International Ice Patrol (IIP) Reports were examined for the years 1966 to 1976. Earlier reports have been studied by Anderson (1971) who determined the annual number of bergs crossing different lines of latitude. For the purposes of this study, the area was restricted to the region bounded by 53° and 56°N latitude. From an analysis of both sources of information it was determined that in an average year slightly more than 400 bergs would travel through the area. These may be broken down by periods as follows:

December to January	20 bergs
February to March	94 bergs
April to July	205 bergs
May to September	93 bergs

The observed maximum monthly frequency in the area occurred in June of 1969 when 632 bergs were counted. In that year, a total of 1430 bergs were seen in the area. It must be realized that these figures are based on overflights conducted by the IIP and as such are strongly dependent on the number of flights and the coverage of each flight. In several years, there were no recordings of berg sightings for a number of months simply because no flights were conducted in the area. It is felt, however, that the seasonal trends are realistic and present a

picture of the relative risk associated with icebergs for various periods of the year.

4. ICE NAVIGATION EXPERIENCE IN OTHER AREAS

4.1 Introduction

A review of the literature and a number of interviews were conducted to determine the status of year-round navigation in other areas. A considerable amount of information is available on navigation in the Gulf of Bothnia, and several reports were obtained from the Finnish-Swedish Winter Navigation Research Board. While year-round navigation is not yet a reality in the Canadian Arctic, plans are underway to establish LNG terminals in the high Arctic and move liquified gas by means of icebreaking tankers in a year-round operation. Activity in the northern waters of the USSR is briefly discussed although little information on any new developments in ice navigation is available.

Ice navigation experiences in southern Canada are also addressed with specific references being made to the Gulf of St. Lawrence and the Newfoundland ports of Corner Brook and Botwood. The Great Lakes navigation extension program is also considered and the latest developments reviewed, and experiences in Alaska and Norway are referred to briefly.

4.2 Gulf of Bothnia

4.2.1 General Description

The Gulf of Bothnia lies between Sweden and Finland and is the northern extension of the Baltic Sea. The Gulf, which consists of the Bay of Bothnia to the north and the Sea of Bothnia to the south, is situated between 60°N and 66°N latitude. Both the Bay and Gulf are relatively shallow with mean water depths of 42 m and 69 m respectively,

and the water salinity which is low due to the substantial river inflow, ranges from 3⁰/oo to 5.5⁰/oo. Normal January to March air temperatures vary from -5°C in the south to -10°C in the north. Ice growth starts in the north in November and usually reaches its maximum extent by early March after which melting starts. All ice has normally disappeared by the beginning of June. The typical level ice thickness in the Bay of Bothnia is 0.5 m - 0.7 m and in the Sea of Bothnia 0.2 m - 0.4 m. Strong winds associated with low pressure systems cause deformation of the ice, and a considerable percentage of the area is covered with rafted, ridged or hummocked ice. Ice ridges often penetrate to 10 m below the surface, and in the Bay of Bothnia pressure ridges to depths of 25 m - 30 m have been observed (Udin, 1975). The ridged area constitutes consolidated pack ice which is surrounded by fast ice along the Swedish and Finnish coasts, and ships transitting the Gulf, in particular the northern part, are often required to break through a substantial ridged area.

While the level ice thickness in the Gulf of Bothnia is less than that in Lake Melville, ridging is more frequent and widespread in the former location because the ice is more susceptible to wind and water movements throughout the winter. The ice in Lake Melville is essentially fast ice and is influenced significantly by wind and water only during the initial stages of formation during which time substantial ridging comparable to that in the Gulf of Bothnia may occur.

4.2.2 Navigation in the Baltic

Ice navigation in the Baltic is described in a paper by Mäkinen and Roos (1977). The normal mode of operation is based on the use of ice-strengthened cargo ships or passenger vessels assisted by government-owned icebreakers, although in recent years more icebreaking cargo ships and tankers of the Finncarrier and Lunni class have been built. Most of the ships used in winter are ice-strengthened to the Finnish-Swedish ice class 1A. In the Gulf of Finland, these ships can operate to some degree without icebreaker assistance, depending on the severity of ice conditions, but in the northernmost part of the Gulf of Bothnia they are wholly dependent on icebreaker support. Typical outputs of the Swedish-Finnish modern icebreakers range from 5.5 Mw (7300 hp) to 16.4 Mw (22,000 hp).

One of the earliest icebreaking cargo ships to operate in the Gulf of Bothnia, the MT KIISLA, has a deadweight of 5750 tonnes and propulsion power of 3.7 Mw (4960 hp) and was designed for operating independently of icebreakers in light ice conditions (Marine Media Management, 1974). While this ship performs better than ice-strengthened cargo ships of the same displacement, it is evident that the KIISLA is not capable of operating independently in the northern part of the Gulf of Bothnia. The Lunni class, however, has been designed to operate in all but exceptionally severe ice conditions, including the northernmost part of the Baltic, without icebreaker support. Four such icebreaking tankers had been built up to 1977 each having a deadweight of 16,000 tonnes and power output of 11.2 Mw (15,000 hp) with an open water speed of 7.5 m/s

(14.5 knots). Mäkinen and Roos describe the performance of one of these ships to the port of Kemi and the northern part of the Gulf of Bothnia during March, 1977. The maximum level ice thickness through which the ship can proceed in a continuous mode is 1 m, and on this trial, thicknesses ranged from 0.5 to 0.9 m. The speed in ice of such thicknesses ranged from 5.4 m/s (10.5 kts) to 2 m/s (4 kts). In a ridge of calculated thickness 8.5 m, the ship had to resort to ramming and five rams were required before the ship finally broke through. It was concluded that this ship, which is classed as 1A Super according to Finnish-Swedish ice class rules, performed essentially as predicted and showed that it could operate without icebreaker assistance in average ice conditions in the Gulf of Bothnia.

4.3 U.S.S.R

The coastal waters of most of the Soviet Union are bound with ice for six months or longer. The largest northern port, Murmansk, is operational year-round. The western part of the Barents Sea is influenced by the Gulf Stream and so traffic into and out of Murmansk in the winter generally operates around the northern Scandinavian coasts and for the most part is not affected significantly by ice. Ice conditions to the west and along the Siberian coast are severe, however, and only the larger Soviet icebreakers can negotiate the region. Unfortunately, very little published information is available on the winter operation in these northern regions. It is known that, up to recent years, ports west of Murmansk were closed for up to 6 months during winter; however since 1970, there have been continual and determined efforts to extend

the season at both ends (Armstrong, 1979). During the navigation season, there is a large east-west movement of goods in the Soviet Arctic which is highly developed in comparison to the Canadian Arctic, and numerous ice-strengthened cargo ships of 5 to 10 thousand tons capacity are used in these polar operations. Major Arctic ports are being dredged and made capable of accommodating cargo vessels in the order of 20,000 tons and more. The Soviets are working towards a year-round navigation season in the Arctic and realize a need for more and larger port and harbour icebreakers. They already have the largest icebreaker fleet in the world with some 35 to 40 icebreakers ranging in power from 4 Mw (5400 hp) to 54 Mw (75,000 hp) (Lawrence, 1979).

4.4 The Canadian Arctic

Ice conditions in the Arctic are generally more severe than those in the study area essentially due to thicker first-year ice and substantial formations of multi-year ice. The navigation season is limited to summer operation and is largely related to the resupply of northern communities and commercial shipping from Churchill, the western Arctic shore and Baffin Island. About one half of the Canadian Coast Guard's annual icebreaking costs are expended in Arctic support (Leask, 1979). The icebreaking cargo ship, MV ARCTIC, went into operation in 1978 and is intended to operate independently of icebreaker support in Arctic regions between June and November. This vessel is designed to operate continuously in 0.6 m of ice and has a displacement of 38,100 tonnes and a shaft power of 10.8 Mw (14,770 hp).

While seasonal navigation and the transport of various bulk products have been occurring for several years in the Arctic, year-round navigation has been stimulated by the discovery of natural gas in the Arctic Islands, and a pilot study (the Arctic Pilot Project) has been initiated to prove the feasibility of transporting liquified natural gas (LNG) from a processing terminal at Bridport Inlet on Melville Island to the Canadian east coast. The LNG would be carried in two class 7 icebreaking tankers each of which would have a power output of 112 Mw (150,000 hp) (Cammaert et al., 1979).

Bridport Inlet is roughly semi-circular in shape with a total area of about 93 km^2 (35 mi^2) and has an entrance about 3.0 km (1.9 mi) wide. The ice, which in the inlet is shorefast, grows to about 2 m in thickness, and there is little effect of wind or tidal action on the ice cover. The inlet is clearly small compared with Lake Melville and one would expect ship movements, especially large tankers, to be relatively constrained. While ice problems around a dock might be similar in both cases, for example, it is anticipated that a ship moving through Lake Melville ice will have fewer constraints once irregular formations have been surmounted.

Other aspects of year-round navigation in the Arctic, such as improved techniques for the detection of icebergs, growlers, multi-year floes, leads, etc., will have direct relevance to winter transport in the study area.

4.5 Gulf of St. Lawrence

Year-round navigation exists in the Gulf of Lawrence in various forms. Ferries travel the Cabot and Northumberland Straits while bulk carriers and tankers travel to and from various ports from the west coast of Newfoundland to the St. Lawrence River. The Gulf is seldom completely ice covered even during the coldest winters with the normal mid-winter pattern being one of relatively light ice and open water leads in the north and heavier more closely-packed ice in the south. Ice formed in the northern Gulf tends to be moved southward by prevailing winds and by the southerly flowing Gaspe Current. The ice accumulates and thickens in the area between the Magdalen Islands and the mainland (Bradford, 1972). Pressure, winds and currents can cause considerable deformations, and while the maximum level ice thickness is less than 1 m throughout the Gulf, rafting and ridging result in much greater thicknesses. Thicknesses of close to 4 m have been observed in the Northumberland Strait, for example (CN Marine, 1979). There is considerable variability from year to year with conditions ranging from no ice being recorded in the Cabot Strait in 1969 to heavy conditions occurring in 1979 with the resulting delays experienced by ships beset in the ice.

The support of shipping in the Gulf of St. Lawrence represents a major icebreaking commitment for the Canadian Coast Guard and the bulk of the force is concentrated there. While conditions in the Gulf are generally handled without great difficulty, at times even the largest icebreakers have trouble under severe pressure conditions. The use of

aircraft reconnaissance and routing plays an important role in the Gulf operation. All ships inbound through the Cabot Strait are required to report their estimated time of arrival at least 48 hours before arrival. The ship is then instructed as to its rendez-vous or convoy assembly point if it is being escorted, or if its power and size preclude the need for support, it will be given the best route to its port of destination.

4.6 Great Lakes - St. Lawrence Seaway

The Great Lakes and St. Lawrence River and the connecting channels have served as a vital transportation corridor and essential commercial transportation link to the United States and Canada's hinterlands since the 1800's. Historically, navigation of the system has been suspended during the winter from mid-December to early April although vessel movement does take place, in varying degrees, during the period normally considered the winter close-down period. Intra-lake commerce, such as car ferry operations and the movement of various industrial products, take place throughout this period on most lakes and connecting channels.

Ice formation on the Great Lakes usually begins about the first of December in the northerly portions of the lakes and is prevalent throughout the system by early January. However, because of their large heat storage capacities, Lake Superior and Lake Ontario rarely freeze over completely and frequently contain large areas of open water. Ice thicknesses greater than 1 m are common in many harbour areas in Lake Superior. As the ice cover moves, it rafts and forms ridges which in

some areas may reach a height of about 8 m above the ice surface and become grounded on the bottom 9 m to 12 m below the surface. On the St. Lawrence River, ice usually forms first along the south shore canal between Montreal and Lake St. Louis in December and advances upriver to Lake Ontario. Mid-water conditions usually consist of fast ice which is not usually affected by wind or current conditions. Ice thicknesses in channel sections may average 0.6 m to 0.9 m while lake and river ice may reach thicknesses of 0.5 m to 0.8 m.

Although a considerable portion of the Great Lakes may be essentially ice-free during winter, certain regions along the traditional routes of bulk carriers become so congested with ice that passage is severely hindered. These regions, rivers and straits where ice tends to collect and jam are known as "bottleneck" areas, and the passage of ships through these areas depends upon a number of conditions such as the frequency of ship passage, degree of refreezing in the ship track, intensity of wind, pressure in the surrounding ice sheet, and depth of ice in the ship track.

Lakes Superior, Michigan and Huron experience problems with rafting and shifting ice, particularly at harbour entrances and in established navigation tracks. Heavy ice conditions are experienced at the northern end of the lakes and bays. Major ice problems in Lake Erie are caused by shifting ice conditions, particularly along the south shore harbour entrances and in the western portion of the lake where ice jams and ice ridges frequently stop vessel transit until icebreakers can reopen the

track. During spring breakup, the loose ice is blown into the eastern end of the lake where it turns into a heavy slush which often provides difficulty for icebreakers and high powered cargo ships. Lake Ontario remains relatively ice free most of the winter with the exception of the eastern portion where prevailing winds tend to build the ice into thick ridges.

In recognition of the potential benefits of an extended navigation season on the Great Lakes, St. Lawrence River System, the United States Congress in 1965 authorized the U.S. Army Corps of Engineers to investigate and conduct a limited study of the feasibility of means of extending the season. The study, which was completed in 1969, concluded that technology at that time was sufficiently advanced to make winter operations physically feasible. A more detailed study investigating all aspects of winter navigation and the legal and environmental ramifications was then authorized in 1970 and the final report of this study is scheduled for completion in 1980 (U.S. Army Corps of Engineers, 1979). While the design of appropriate bulk carriers and icebreakers has been a part of the overall program (Johannson, 1972, Edwards et al., 1972), the navigation aspects of this study were concerned primarily with ice management techniques in the bottleneck areas described above on the basis that these areas, and not the lake ice itself, constituted the essential impediment to winter navigation through the entire system. Such control techniques have been considered in relation to the potentially undesirable effects of winter navigation such as increased shore structure damage, possible disruption of ferry transportation, and unless mitigated

against, flooding as a result of ice jams which could be aggravated by increased ice buildup in ships channels. Ice management techniques being considered include bubblers which utilize the thermal reserve in the freshwater bodies, floating log booms to control ice movement and prevent jams, thermal discharge from shore installations, and small islands which serve as ice anchoring devices.

In terms of icebreaker support, it is proposed that a total of 5 type B and 17 type C icebreakers be available. Type B is a major icebreaker capable of breaking 0.6 m to 1 m of ice without backing and ramming and type C is capable of breaking 0.5 m to 0.6 m of ice without backing and ramming. These icebreakers would be deployed at strategic points in the lakes along major shipping routes and in areas of heavy ice concentration.

4.7 Alaska

The development of oil and gas resources in Cook Inlet on the south coast of Alaska has created a requirement for year-round shipping. Cook Inlet is about 240 km long and varies in width from 16 km to 80 km. Due to the extreme range of diurnal tides, the inlet does not freeze into a continuous ice sheet but is covered by large first year floes 0.8 km or more in diameter which travel with the tidal current at velocities of up to 4 m/s (9 knots) (Gaither, 1969). Although this ice presents a considerable impediment to year-round navigation in the inlet, two operations have functioned successfully for several years by making use of medium-size shallow draft icebreakers (Bates, 1973).

4.8 Norway

The port of Drammen in Norway is described in the literature as an Arctic port which experiences year-round navigation (Fuglum, 1971). It is situated about 40 km from Oslo at the end of Drammensfjord and about 20 km from the open sea. Every year for a period of 3-4 months, the fjord is frozen to a thickness of 0.90 m to 1.2 m; however, it is considered that the landfast ice presents few problems for navigation with a dedicated icebreaker maintaining open channels to the port.

4.9 Newfoundland

4.9.1 Botwood

Botwood is used as a shipping port for paper produced at the Abitibi-Price mill in Grand Falls. Landfast ice 0.6-0.9 m thick is usually experienced and currents up to 1.0 m/sec (2 knots) exist in the Bay of Exploits. The ice may form ridges in the entrance to the bay under strong winds, and this has often resulted in considerable delay in breaking through the ice. The frequency of winter shipping into Botwood is once every two to three weeks and while the SIR HUMPHREY GILBERT is stationed at Botwood, a small tug is used continuously to keep ice broken up alongside berths and in the turning radius of the berths. Commercial ships such as the IMPERIAL BEDFORD 6.0 Mw (8000 hp) and AXEL HEIBERG 6.7 Mw (9000 hp) are generally able to traverse the area unassisted.

4.9.2 Corner Brook

The ice conditions in Corner Brook are similar to those in Botwood.

Fast ice is experienced in Humber Arm, and pack ice may form outside. The entrance to the Bay of Islands may come under pressure when the ice is influenced by strong onshore winds. The shipping frequency is up to 3 vessels per week at Bowaters and Clark Transportation docks. Bowaters uses a small tug to keep ice near the wharves broken up.

4.10 Implications for the Study Area

In the study area, year-round navigation would entail passage through both landfast and pack ice, the latter containing various concentrations of first year ice, multi-year ice, and icebergs. The primary obstacle to navigation in the landfast ice in Lake Melville would be due to ice ridging and rafting that could occur in the east end of the lake although significant resistance could also be provided by ridging and rafting throughout the lake. In the pack ice, the greatest problems would be associated with high concentrations of thick ice especially when the ice is under pressure.

From the above discussions, it appears that the landfast ice in Lake Melville is not unlike that in the Great Lakes except that the latter is freshwater ice. The ice ridging problem and the level ice thicknesses in Lake Melville are similar to those in colder regions of the Great Lakes; yet winter transportation has been maintained in some parts of the Great Lakes despite heavy ridging. It has been recommended that an icebreaker which is capable of breaking continuously through 1 m of underformed ice is required for year-round shipping support in colder regions of the Great Lakes. It is suggested that a ship of similar

capability would be required to operate year-round in Lake Melville.

The experiences in other areas of landfast ice may also have some relevance for operations in Lake Melville. In Botwood, Newfoundland and Dramen, Norway, ships move through landfast ice throughout the winter. In Dramen, it is reported that a dedicated icebreaker maintains open channels in ice up to 1.2 m thick and in Botwood, the SIR HUMPHREY GILBERT has been used in a somewhat similar manner to break channels through about 30 km of shorefast ice in the Bay of Exploits (Capt. G. Warren, personal communication, 1979). However, experience with channels through fast ice in the Baltic has shown that repeated breakings gradually result in an ice cover thicker than the surrounding unbroken ice sheet. This buildup (which is further discussed in Section 6.3.3) is clearly a function of the frequency of passages, the time between passages and the temperature regime. Bradford (1979) notes that in 1972, the track created by the JOHN A. MACDONALD on Lake Melville re-froze rapidly reaching a thickness of almost 0.40 m in 72 hours.

It is more difficult to extrapolate from the experiences in other regions to navigation considerations in the Labrador pack. This is due to the dynamic nature of the pack and the various ice forms which compose the pack and constitute significant hazards to navigation. Ice conditions in the Gulf of St. Lawrence, while at times presenting problems for winter navigation, are not as severe as in the Labrador pack and do not normally exhibit features such as multi-year ice and icebergs. In

addition, sea ice pressure is likely to be less severe in the Gulf than off Labrador.

Further insight into winter operations in the Labrador pack may be gained by observing the experiences of Baltic ships. In the Gulf of Bothnia, the landfast ice in the extreme north may grow to 1 m in thickness while the central pack area experiences considerable ridging and rafting which frequently increase the ice thickness beyond 10 m below the surface. While Baltic ice is susceptible to a degree to wind and water movements, the Labrador pack is more dynamic and generally contains thicker ice. It is thus expected that ships which operate effectively in the Baltic ice could, at times, experience greater difficulty in the Labrador pack. From the above discussions it has been seen that the largest icebreakers in the Baltic have a power output of 16.2 Mw (22,000 hp) and are capable of coping with the worst ice conditions in the Baltic. It is likely that icebreakers that can operate effectively in the Labrador Sea in a year-round operation will require powers of similar magnitude. Further considerations of appropriate ships for the study area are addressed in Section 5.3 of this report.

5. NAVIGATIONAL CONSIDERATIONS IN THE STUDY AREA

5.1 Introduction

In this section of the report, the experiences and opinions of a number of seasoned ships' masters concerning the problems associated with year-round navigation in Lake Melville are presented and general considerations of the type of ships required to effectively operate in the area are made. In order to document relevant experiences and opinions, NORDCO retained the services of Edward Anthony Marine Consultants Limited. Captain Anthony has used his and others experiences to relate the problems associated with transportation into Lake Melville and to make general observations on navigational aids and radar performance in the area. A number of interviews were conducted and the logs of a number of ships that have operated in the study area were reviewed for voyages made during ice conditions. It should be noted that the experiences related have been documented primarily by captains who, while having had considerable experience with various types of cargo, passenger ships and icebreakers in various ice conditions on a year-round basis in other areas, have not by and large operated a ship in the study area during the closed season. While first-hand knowledge can be conveyed of experiences in the study area during freeze-up and the sealing season in March, in general, opinions of the viability of year-round navigation into Lake Melville are extrapolations of such experiences. It should also be pointed out that most such experiences have been obtained in relatively low-powered vessels that are not suitable for the conditions existing in the study area in winter. To supplement these experiences, general considerations of ships suitable for such

conditions are made here from an analysis of the ice conditions in the study area. In addition, a very preliminary design of a range of ice-breaking cargo ships is presented in Appendix B. This design is the result of a brief investigation by German and Milne of Montreal who were contracted by NORDCO to undertake this task.

5.2 Review of Experiences and Opinions

5.2.1 General

The following is a summary in point form of the general experiences and opinions of a number of ships masters who are familiar with the study area.

1. The pack ice represents possibly the greatest hazard to year-round navigation in Lake Melville, and extreme caution is recommended when navigating in it. The greatest hazard with this ice might be encountered at the outer edge of the pack where there is often a heavy swell in the water which causes the ship to pitch and roll at the ice edge as an attempt is made to enter the pack. The presence of multi-year or glacial ice at this edge compounds the problems of entry into the pack. It is thus recommended to enter the ice at low speed to receive the initial impact, and once into the pack, speed should be increased to maintain headway and control of the ship.
2. In any shipping operation into Lake Melville during winter, some delays will have to be accepted. Ice conditions are influenced by wind and change with the passage of storms, and at times a change of wind will be required to loosen the ice in the approaches to Hamilton Inlet to allow passage.

3. The main obstacles to navigation in Lake Melville occur when strong winds cause the ice to raft and ridge in the eastern end of the lake during freeze-up. Once the initial freeze-up is completed, the ice is stationary and a track could be made and kept open by a dedicated icebreaker.
4. Probably the most hazardous conditions to a ship, and more especially a ship having an inexperienced ice master, is in very loose, heavy ice in late spring during poor visibility. It is very easy to develop excessive speed under such conditions.
5. At Eskimo Passage and throughout Rigolet Narrows, caution should be taken with regard to currents. A rate of up to 2.5 m/sec (5 knots) at spring ebb tides and 2 m/sec (4 knots) at flood is not unusual. While from an examination of the charts, Pike Run appears to be a better passage, excessive currents and several whirlpools have been experienced there, making navigation very difficult and dangerous. Transit of Eskimo passage should be made at slack water and speed should be adjusted accordingly in Groswater Bay to avoid waiting in the Narrows entrance.

5.2.2 Navigational Aids in Study Area

The Labrador coast, as is apparent from any marine chart, is very poorly equipped with regard to navigational aids. The appearance on the charts of a dozen or so lights is rather deceptive as many of these lights are merely blinkers from atop small poles lashed to the sides of cliffs. It is easily possible to pass extremely close to many of these lights (in the order of one (1) mile off) and be barely able to see

them even when directly abeam. During snow squalls and other conditions of poor visibility, it would be impossible to see these lights at even shorter distances. The present light system is of little or no value to the navigator.

Radio communication in Hamilton Inlet is reasonably good because of the Cartwright Coast Guard Radio. The one problem with this particular station is that to date it cannot accommodate duplex calls. V.H.F. facilities at Goose Bay Coast Guard Radio are presently quite good until one reaches Green Island in the lower end of Lake Melville but are ineffective after that when heading seaward. These facilities could be improved through a system of relay stations and then be utilized as far seaward as the outer approaches to Groswater Bay. There are two D.F. Radio Beacons, one located at each side of the entrance to Hamilton Inlet

In general, the area is deficient with regard to navigational aids and would require upgrading to support a year-round operation.

5.2.3 Radar Performance

Experience has shown that the presence of ice and snow in an area will sometimes give a very distorted picture when compared with the same area in ice-free water. Rough ice can actually give the effect of a solid target and thus make the identification of low rocks and islands impossible.

In general, icebergs are usually good targets if they have vertical faces, but when the berg presents a face which is smooth and sloping, a specular reflection may occur in an unfavorable direction and no echo will be returned to the antenna. Cases are reported of bergs looming so large to the eye that it would seem impossible for them to escape detection by radar. Berg echoes can change much in strength as a vessel is passing them due to the changing aspect. However, growlers present probably a greater danger because their low height and size make them a poor target which may not be detected until at very close range in heavy sea conditions. The range is often so close that it is within the sea-clutter area on the radar screen.

Nevertheless, radar does have its usefulness when used to navigate through ice fields. A good observer can easily manoeuver a ship through an ice field and avoid the pressure ridges which are very detectable if the snow cover is not too deep. If one uses the radar on a reasonably low scale (say 1.5 miles) leads and very smooth sheets of ice can be quite easy to identify. This, of course, allows one to carry on during hours of darkness or during foggy conditions without encountering heavy ice conditions and pressure ridges. In a convoy situation, with radar on a very low range it is very easy to follow the track of an icebreaker and still maintain good control over the distance between the two ships.

5.3 Ship Considerations for the Study Area

Year-round navigation into Lake Melville implies that a vessel will be required to negotiate a wide range of ice conditions. It has been seen in previous discussions in this report that in many cases, it is difficult to quantify the ice conditions in the Labrador pack simply because of the lack of good information. The relatively simple matter of an average ice thickness is, for example, not documented in sufficient detail from in-situ measurements over a sufficiently long period to allow one to categorically specify a representative thickness for ship design based on ice resistance. This is not, of course, true of Lake Melville where the ice is landfast after complete freeze-up and changes little over the winter once the initial deformations have occurred. In addition, general ice thicknesses in Lake Melville could be predicted with some confidence from thermodynamic considerations, whereas conditions in the pack are sufficiently dynamic to introduce a considerable lack of confidence if this method were applied to that regime. In addition to the lack of information on ice thicknesses, the degree of roughness and deformation of the Labrador pack during various months needs further documentation in order to determine the extent to which a ship would be required to travel through such non-uniform ice which would result in an increase in resistance to passage.

Besides the design limitations imposed by ice conditions in the study area, it is also necessary to consider bathymetric limitations and channel restrictions along the route. This is especially important for the design of cargo vessels in which the capacity is to be maximized

while costs are minimized. This is probably most easily accomplished by increasing draft rather than length; however in the study area, the draft would have to be limited to less than 12.5 m since the recommended track in Groswater Bay has been wireswept to only that depth while the minimum depth at The Narrows is slightly greater at 13.4 m. While these depths are not of major concern for the design of icebreakers per se, they would certainly require consideration for the design of icebreaking cargo vessels and bulk carriers.

While the purpose of this study is to investigate the problems associated with year-round navigation into Lake Melville and is not as such concerned with ship design, it is necessary, nevertheless, to consider the basic criteria involved in determining an appropriate ship for the ice conditions of the area. In the first instance, the design of a vessel for navigation in ice will be determined by the desired speed of the vessel under certain ice conditions. The desired speed is determined by the economics of the operation and is generally considered to be limited to a minimum of 3 to 4 knots in continuous ice. The capability of an icebreaking vessel is usually expressed in terms of the thickness of ice that the vessel can break in a continuous mode of operation. Ice strengthened vessels with such classifications are considered to be capable of operating in ice of that thickness without icebreaker support. With the support of a more capable vessel, ice-strengthened ships should be capable of operating in ice about 50 per cent thicker, and in the case of two ships of equal class working together, they could be capable of operating within areas and seasonal limitations assigned to the next highest class (Bustard, 1973).

For the case of two ships of equal class but different displacements, it is found that the performance of the larger ship will be better in non-uniform ice which is thicker than the design uniform thickness because the larger ship represents a greater store of energy. Ridges which the larger ship may traverse without stopping will cause the smaller ship to resort to ramming in order to break through. This was borne out in 1970 with the experience of the MANHATTAN and the LOUIS ST. LAURENT, both of which are class 4 vessels with comparable performances in breaking continuous uniform ice. The MANHATTAN was capable of passing through four or five ridges without stopping while the ST. LAURENT had to resort to ramming each time.

Various criteria have been used by different agencies to determine the power of a vessel in certain ice conditions. Lloyds of London make power a function of vessel length and beam for the case of a ship moving through uniform ice (Bustard, 1973). The Finnish-Swedish Board of Navigation rules make power a function of displacement with the cut-off value being where the displacement and power are sufficient for continuous operation in the conditions envisaged (Finnish-Swedish Ice Class Rules, 1971). More recently, developments in ice resistance theory have led to the conclusion that the required power for continuous icebreaking is primarily a function of ship parameters and ice thickness. By carrying out full-scale tests on existing ships, it is possible to obtain a relationship which may be used for preliminary design purposes. (The reader is referred to Chapter 6 and Appendix A for detailed discussions of ice resistance theory).

Bustard (1973) suggests a simple relationship of the form

$$P = CBh^2$$

where P is the shaft power

B is the beam

h is the ice thickness

and C is a constant approximately equal to 527 kw/m³ in SI units
and 20 hp/ft³ in British units.

For year-round navigation supporting an industrial operation in Lake Melville, it is considered that two modes of operation are possible, and the advantage of one over the other will depend on economic considerations. Either an icebreaker could be used as an escort for an ice-strengthened cargo ship, or the cargo ship itself could be an icebreaker. Whichever method is used, it is considered that based on the ice conditions described in Section 3.4, for an effective operation a Class 4 vessel is the minimum requirement for icebreaking. The power of such a vessel would depend on a number of factors, but a preliminary estimate based on the above equation indicates that for a beam of 20 m, the power would be in the order of 16 Mw (21,000 hp). The selection of a Class 4 vessel is based on the assumption that the average thickness of uniform ice is 1.2 m (4 ft) and that ice thicknesses greater than this are associated with non-uniform ice which will provide less resistance to movement per unit thickness. It is also assumed that the vessel will be capable of manoeuvring around ice formations which would require a prohibitively high time to break.

Based on the observation discussed above that ice-strengthened ships should be capable of operating in ice 50 percent thicker than the uniform design ice thickness when accompanied by a more capable vessel, a Class 3 ice-strengthened ship would be capable of year round operation when supported by a Class 4 icebreaker. However, during periods of heavy ice pressure, the rate of closure of the icebreaker track may be sufficiently high to make it difficult for an escorted ship to follow the icebreaker at a safe distance. In such cases, the ships would have to wait until the pressure on the ice was relieved.

In Appendix B, a preliminary design of a number of icebreaking cargo ships is presented. These ships which are considered to have cargo capacities of 10,000, 20,000 and 30,000 tons are Class 4 vessels and have power outputs ranging from 14.6 Mw (19,600 hp) to 18.2 Mw (24,400 hp) and displacements from 15,310 tons to 41,200 tons. While each of the three vessels is based on a design speed of 1.5 m/sec (3 knots) in 1.2 m of uniform ice, the higher displacement vessel will travel more effectively in heavy ice formations which are beyond the design thickness and will not be required to resort to the ramming mode of icebreaking as frequently as a ship of lower displacement.

In terms of economics, an icebreaking cargo ship has higher capital costs and is more expensive to operate in open water than an ice-strengthened cargo ship of similar capacity. It is likely that these cargo ships will spend only a small percentage of their operational time in ice conditions, and a very careful design study would be required to

minimize the weights of the structure and machinery to ensure that they are not too uneconomical when operating in open water. The costs associated with this operation would have to be compared with the cost of providing a dedicated icebreaker to support an operation based on ice-strengthened, rather than icebreaking, cargo ships.

It would be possible to extend the navigation season beyond the present six months but not year-round by using ice-strengthened ships of lower ice-breaking classes. The main obstacle during early winter would be ridging in Lake Melville, and if this could be surmounted by an appropriate icebreaker, ships of Class 2 rating could continue to operate well into January. At the end of January, the ice thickness in the lake is typically in the order of 0.7 m, and the ice in the pack at that time is generally of a lower thickness. While ice pressure generation could lead to some delay, it is anticipated that Class 2 ships would be capable of operating effectively up to this time. Similarly, if an icebreaker were assigned to Lake Melville in late May, early access could be achieved by such vessels. It is suggested, however, that based on the experiences of the JOHN A. MACDONALD in May 1967 and 1972 as discussed in Section 2.3 and general ship design as discussed above, an icebreaker of greater capability would be required for an efficient operation. Pack ice conditions at this time, while being generally of low concentration, will consist of thick first year floes interspersed with multi-year floes (as discussed in Section 3.4) and due consideration will have to be given to these features.

5.4 The Use of Explosives to Facilitate Icebreaking

In this section of the report, consideration is given to the possibility of using explosives to create a path for an icebreaker if it were stuck in a large ice formation. This might be especially appropriate in Lake Melville, as opposed to the pack ice, since the landfast ice would provide a more stable platform from which to deploy the explosives. While there are possibly other means of allowing free movement of a vessel in such ice conditions, most methods are in the conceptual stage only, and therefore not appropriate to this discussion.

The use of explosives to enable ships to move in heavy ice conditions is quite old. Sealing ships operating in Newfoundland and Labrador waters have used this technique for many decades (sometimes with disastrous results). Several experiences have shown that to achieve the best effect from explosives, it is necessary to deploy the explosives under the ice cover at some depth which is dependent on the ice thickness.

Frankenstein and Smith (1970) report on the use of explosives to remove ice jams primarily in rivers. They report that the use of explosives for destroying jams goes back to 1758 and that the most common explosive has been 40% dynamite with the usual practice being to place two to twelve sticks within the jam. The early use of explosives in ice work in Canada has been reported by Barnes (1928) who used thermit as the destructive agent.

During the 1960's Frankenstein and Smith report that the U.S. Army effectively used a newly developed explosive, ANFO (Ammonium Nitrate Fuel Oil), to remove ice jams. It was found that the best results were obtained when the charge was placed at a distance below the ice surface which varied as the cube root of the charge weight and that the resulting hole diameter depended on the charge weight in a similar manner. The most efficient method for the removal of river ice jams was to place between 10 and 20 charges under the ice and detonate them simultaneously, the spacing of the charges being one hole diameter. In this manner more than a mile of river ice could be broken up in an eight-hour period.

Further study on the use of explosives for breaking ice has been reported by Goode and Teller (1971). They suggest that, when attempting to break ice over a large area, it is necessary to obtain displacement of the total cover at the same time, and this can only be obtained if the charge is placed in the water beneath the ice cover. The authors report that experimental data suggest that the charge be placed twice the distance into the water as the thickness of the ice and that the charge weight be numerically equal to twice the distance of the charge from the top surface of the ice. They caution that allowances must be made for different circumstances, and note that it is unlikely that ice formations which are thicker than about 5 m can be broken and scattered with a sub-surface charge. For massive formations, it is suggested that standard drilling and blasting be used. It is concluded that with the use of explosives, and fail safe techniques, ports and shipping lanes which are now closed to traffic could be kept open for longer periods.

One method of doing this would be to deploy "sleeper" charges in critical areas during the open water season and detonate them as required during excessive ice conditions.

It is entirely possible that the use of explosives might have application to ice formations in the study area from time to time. However, the inherent dangers associated with the deployment and operation of such devices must receive appropriate consideration.

6. TRANSIT TIME ANALYSIS

6.1 Introduction

In order to determine the performance of various types of vessels in the ice conditions typical of the study area from freeze-up to breakup, a transit time computer model was developed. This model was based on icebreaking and ice resistance theory for ships operating in a number of icebreaking modes. The basic ice coverage data were obtained from the AES Ice Central Charts for the years 1969-79 inclusive. This data source is essentially the only one available that can provide ice information in the Labrador pack over a period of several years. It is appreciated that the information portrayed on these charts is on a fairly large scale and will often not show the detail of features which could be important for navigational purposes. Thus, while large areas of open water are reported on the charts, often smaller leads which a ship could take advantage of may not be shown, and as a result any predictions of transit time would, in the first instance, be pessimistic. It is worth noting however, that while icebreakers are quite capable of following leads and manoeuvring around certain ice formations, large cargo ships do not have a similar capability and are much more prone to continue on a "straight-line" course. Also of considerable importance are the occurrence and severity of ice pressure in the pack ice. As pointed out previously, almost no quantitative information is available on this phenomenon in the Labrador pack, and the neglect of it in any prediction of transit time will lead to optimistic results.

During the initial stages of the study, a search of available transit models was undertaken; however, it was soon learned that few such models existed for the type of conditions typical of the study area, and most of these were of a proprietary nature or were based to such a degree on empirical results as to be of little benefit to the present study. A thorough review of ice resistance theory was then carried out, and subsequently a transit model was developed in-house. This model is capable of determining ship performance in ice conditions ranging from low concentration pack ice to a continuous ice cover. The model is described in detail below, and the basic assumptions and limitations of the model are also documented. A brief discussion of the basic ice resistance theory used in the model is given below, and a more thorough treatment of the various theories is attached as Appendix A.

6.2 Ship Performance in Ice

While efforts to describe the process of icebreaking and ship movement in ice have been made since the late 19th century, in many ways the process is still not properly understood and further work is required. A number of people, mainly in Canada, U.S.A., U.S.S.R., Finland, and Germany, have studied the question in detail and, recently, a large number of model and full-scale tests have been conducted albeit in mainly continuous uniform ice conditions with only little effort being applied to pack ice of different concentrations and floe sizes. In addition, only recently has any significant effort been applied to the effect of ridges on ship movement, most of the work in this area having been carried out in the Baltic in the last five years.

Probably the most significant work on the behaviour of a ship moving in a uniform continuous ice cover has been conducted by Kashteljan et al. (1968) who stated that the resistance to movement is due to three different components; viz., the resistance due to the actual breaking of the ice, the resistance due to turning and submerging the broken ice pieces and the resistance which depends on the velocity of the ship. Most ice resistance equations developed in the last ten years have been based on Kashteljan's concepts. However, many of them are of an empirical nature because the basic physics of ice breaking is not understood well enough to allow a reliable theoretical formulation. In these empirical equations, there are considerable combinations of parameters and indices. Indeed, both the values and combinations of the parameters and indices vary depending on the particular equation's developer and the ship for which it applies. One must therefore be careful when applying an equation to a ship which is not similar to that for which the equation was derived.

While there is considerable disagreement among various people in the field on the dependence of the resistance components on ship and ice parameters, there is, in general, agreement on two points:

- the overall resistance varies linearly with the beam of the ship
- the ice-breaking component is a relatively small part of the total resistance which implies that the strength of the ice is not of major importance.

Disagreement concerns mainly the exact dependence of the resistance on the ice thickness and speed of the ship. Some researchers find that the resistance varies linearly with the ice thickness while others find mainly a second power dependence. Similar variations occur with the relationship between resistance and ship velocity. Such variation could lead to significant differences in predicted ice resistance and ship performance. The reader is referred to Appendix A for further discussion of these points.

In the review of the various ice resistance equations for movement in a continuous ice cover, the basic selection criteria of a suitable equation were that (i) the equation should accommodate the maximum number of ship and ice parameters that are considered to have an influence on the resistance; and (ii) the equation should have a minimum number of empirical constants and coefficients which might limit its application. Based on these criteria, it was found that the equation of Enkvist (1972) for movement in a continuous ice cover was the most appropriate equation for the present study. This equation was initially applied to the CCG icebreaker, LOUIS ST. LAURENT, to compare the calculated speed in continuous ice of various ice thicknesses with the known capabilities of this ship from published sources. It was determined that the Enkvist equation was optimistic and resulted in higher speeds than experienced in actual ice conditions of the same thickness. The equation was then modified to give more realistic predictions of speed, and this modified form was used throughout the program for ships operating in a continuous ice cover.

As mentioned earlier, the transit model would necessarily have to accommodate the performance of a ship operating in pack ice and heavy formations such as ridges which would prevent movement in a continuous mode. A review of the literature indicated that little work has been carried out on the resistance of a non-continuous ice cover to ship movement, and that the most significant work has been due to Soviet researchers. In Canada, German et al. (1975) proposed a relationship which related ship speed in an ice floe field to ice concentration and ship speed in open water and in a continuous ice cover. This equation is limited to ice concentrations greater than 5/10 and relates movement in a floe field to movement in a continuous ice cover. Buzev and Ryvlin (1966) developed an empirical relationship, based on laboratory and field observations, to calculate ice resistance under various conditions. The resistance was expressed as a function of ship speed and ice floe thickness and area. This equation was modified by Kashteljan et al. (1969) to include an empirical constant based on floe diameter. The resulting relationship was seen to produce results in close agreement with the observations on the LOUIS ST. LAURENT (Noble et al., 1978). A modified form of this equation, to allow for differences in concentration, is used in the model for this study. Bronnikov (1959) developed an expression based on full-scale tests of a Soviet Arctic cargo ship, but this relationship is limited to ships of a similar category.

It is generally agreed that the resistance to motion of a ship in ice decreases rapidly as the ice concentration decreases and becomes quite small for concentrations less than 6/10 when small floes can be

pushed aside rather than broken. At higher concentrations (probably to 8/10), it will often be possible to make detours around large floes which would otherwise provide significant resistance. Measurements conducted on the LOUIS ST. LAURENT indicate that the resistance in 9/10 ice 0.9 m thick is about one-third the resistance in a continuous ice cover of the same thickness (Noble et al., 1978).

The effect of snow cover on resistance to ship movement in ice has not been studied in much detail and the ice resistance equations usually simply allow an increase in the coefficient of friction to accommodate the increased resistance to snow-covered ice. It is well known that snow cover can cause a marked increase in resistance even in relatively thin ice, but until further study is conducted in this area, a somewhat arbitrary increase in frictional effects in the ice resistance equations appears to be the most satisfactory way to accommodate it.

When a ship encounters ice resistance which is greater than the thrust available from its propellers, it cannot operate in the continuous mode and must resort to ramming. In a heavy formation, a number of rams may be required before the ship breaks through completely. The ramming process is one of retreating a sufficient distance to gain momentum, manoeuvring into a favourable position, advancing at speed through the broken channel and breaking through the formation until all the energy has been expended. The cycle is then repeated until the ship breaks through completely.

While there is no direct method to calculate ship resistance during ramming, a number of theoretical investigations and full-scale measurements have been made to analyse the forces which are developed at the bow of an icebreaker during the ramming process (Kasi, 1921; Simonson, 1936; Ferris, 1959; Sodhi et al., 1977). The equation used in this study to determine the advance of the ship during ramming is based on the work of Vinogradov (1946) and White (1965). It expresses the relationship between the forces developed and the extent of advance during each ramming cycle. Details of the development of the equation are given in Appendix A.

6.3 Ship Movement in Built-up Channel

The foregoing discussion points out the deficiencies in the existing capability to predict ship performance in continuous and pack ice conditions. A further complication in the case of a ship moving in landfast ice is the prediction of the ship's behaviour in a previously broken track. A 30,000 ton cargo ship (for example) crossing Lake Melville will break a track in the order of 30 to 40 m wide depending on the beam and speed of the ship and the ice conditions at the time. While the normal thermodynamic ice growth on the lake would result in a thickness at the end of winter of about 1 m, there are three possible processes which could contribute to increased thicknesses in the ship's track. These are discussed below.

6.3.1 Closing of the Ship's Track by Lateral Movement of the Ice Cover

It is conceivable that by cutting the ice sheet on the lake in two,

the combination of tidal cracks and the newly cut ship track may allow portions of the ice sheet to move laterally under the influence of winds or tides. While the closing of the track itself may not cause problems, the potential difficulty may arise from the fact that a portion of the broken ice in the ship's track is normally pushed under the edge of the ice cover on either side of the track creating increased thicknesses at these locations. Subsequent ship passages may be made more difficult by the positioning of these thicker formations due to external forces on the parent ice cover. Of course, this local increase in thickness may be of little consequence during the early stages of the season when the main ice cover may be still relatively thin.

6.3.2 Formation of Ridges in the Ship's Track

If the ice cover were free to move as described above, it is possible that the ice pieces in the ship's track would be compressed between the two portions of the main ice sheet, and depending upon the thickness of the broken pieces in the ship's channel and the forces being applied, may be deformed into a ridge, extending above and below the parent ice cover. Clearly, this phenomenon is much more likely to occur in the pack ice especially when the pack is under pressure. The thickness of the ridge would depend on the initial ice thickness, the wind stress and the concentration of ice pieces in the ship's track.

6.3.3 Excess Ice Buildup Due to Refreezing of the Ship's Track

With repeated passages of ships in a single track, the ice thickness in the track will increase faster than that of the surrounding ice

sheet because of the periodic re-exposure of open water in the track. The thickness at the end of the season would thus be considerably greater in the track than the main ice cover assuming that a single track is used. Because of the manner in which this ice is formed, it becomes a matrix of ice blocks and patches of thin ice and is generally weaker than the surrounding ice sheet. After a certain number of passages, provided that the track retains its original configuration, the accumulation of ice may reach a thickness at which the resistance in the track is greater than in the main ice sheet due to the frictional resistance between the excessively thick ice and the ship hull. This thickness clearly depends on the frequency of ship passages and the relative strengths of the main sheet and the ice formation in the ship's track.

Observations of ship channel ice thickness and the correlation with predicted ice buildup have been addressed by Baltic researchers (Sandkvist, 1978). The ice conditions in Lulea Harbour, Sweden were studied over the winters of 1976-77 and 1977-78 and the buildup of ice in a ship track was compared with the predicted buildup using a mathematical model proposed by Michel and Berenger (1975). In the model, which depends on the number of freezing-degree days, the broken ice in the track is considered to consist of a pile of superimposed ice sheets. In each sheet or layer, a portion is water and the remainder solid ice. It is assumed that the water is distributed evenly from the top surface to the bottom of the broken ice, the ratio of water volume to the total volume of accumulation being the porosity of the formation. It was found in the

Lulea Harbour work that the predicted and measured formations correlated well although the accuracy of the model depends on the choice of layer thickness and porosity.

In order to predict the accelerated buildup in a ship's track in Lake Melville, a computer program was developed using Michel's algorithm and ice growth curves were produced for various frequencies of ship passages. The growth of ice in the ship's track based on a ship frequency of 15 days is compared with the natural thermodynamic ice growth in Figure 6.1. The natural ice growth is determined from the familiar Stefan equation (Anderson, 1961) which is expressed as $H = \alpha \sqrt{\Delta D}$ where α is the heat exchange coefficient, ΔD is the number of freezing-degree days and H is the ice thickness. The freezing degree day record of Goose Bay for a period of 30 years was used and the local heat exchange coefficient (α) was taken as 0.02. This value is consistent with work in the Baltic Sea and agrees with observations typical of a body of water such as Lake Melville.

It is noted that the effective ice thickness in the ship's track is less than the main ice sheet thickness after the first passage because of the high proportion of water in the track following a single passage.

In Figure 6.2, the end of winter ice thickness in the ship's track is shown as a function of ship frequency across the lake. A trip frequency of 15 days will result in a thickness at the end of the winter of 1.5 m while for a frequency of 30 days, the thickness is 1.3 m.

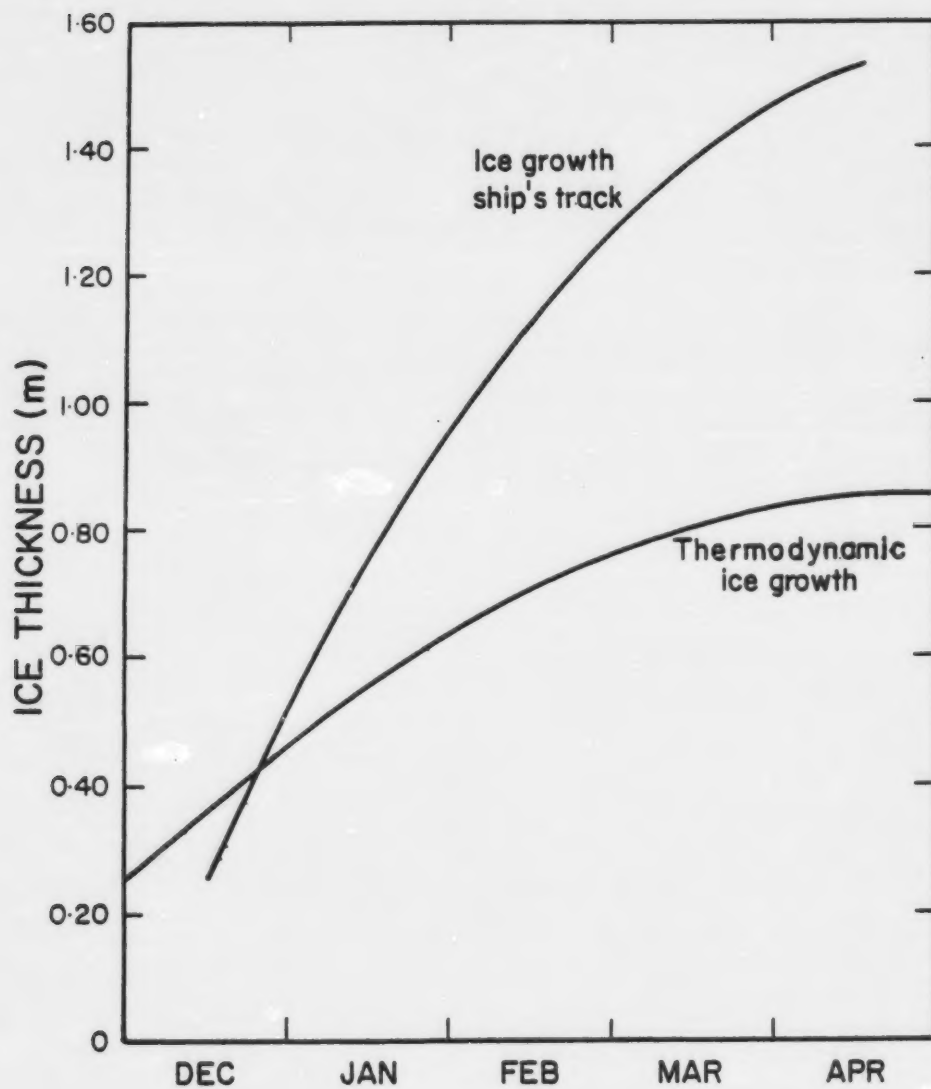


FIGURE 6.1 ICE BUILD-UP IN SHIP'S TRACK
FOR SHIP FREQUENCY OF 15 DAYS

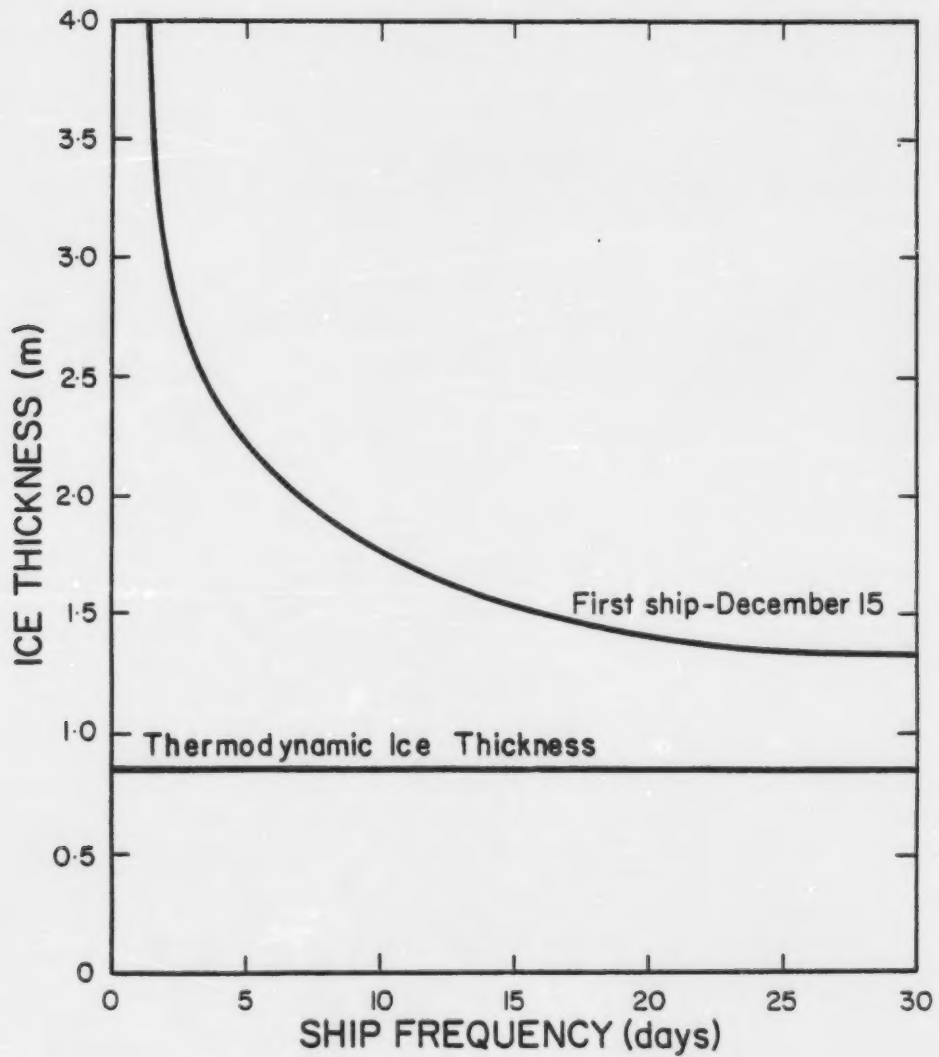


FIGURE 6.2 ICE THICKNESS AT END OF WINTER IN SHIP'S TRACK
FOR FIRST SHIP ON DECEMBER 15

These results are based on the assumption of an initial uniform ice cover over the lake during the first ship passage. It is clear, however, that depending on the dynamics during freeze-up (see Section 3.3) the ice thickness could vary considerably in some areas of the lake. In general the average ice thickness over the entire lake, under average freeze-up conditions will probably be 20 to 30 per cent higher than that predicted from Stefan's Law. In areas of severe ridging the thickness will be several times the average thickness. The buildup of ice in the ship's track will then be greater than that predicted above, and the number of passages through one track may decrease accordingly.

Some idea of the number of ship passages that are likely to be made in one track may be made by comparing the resistance of the normal ice with the resistance of the accelerated ice growth in the track as shown in Figure 6.3 for the LOUIS ST. LAURENT. Due to the broken nature of the ice in the ship track there is less resistance to ship motion than in the original uniform ice sheet. This enables the ship to maintain a higher speed in the track than in a uniform ice sheet of the same thickness.

As indicated by Figure 6.2, the rate of ice build up in the ship track depends on the trip frequency. If a certain trip frequency, for example every fifteen days as in Figure 6.1 is assigned, the ice growth in the track can be determined. It is then possible to ascertain the time of year when the resistance of the ship track is more than the resistance of the uniform ice sheet or conversely the number of trips the ship can make before it must make a new track. By making some

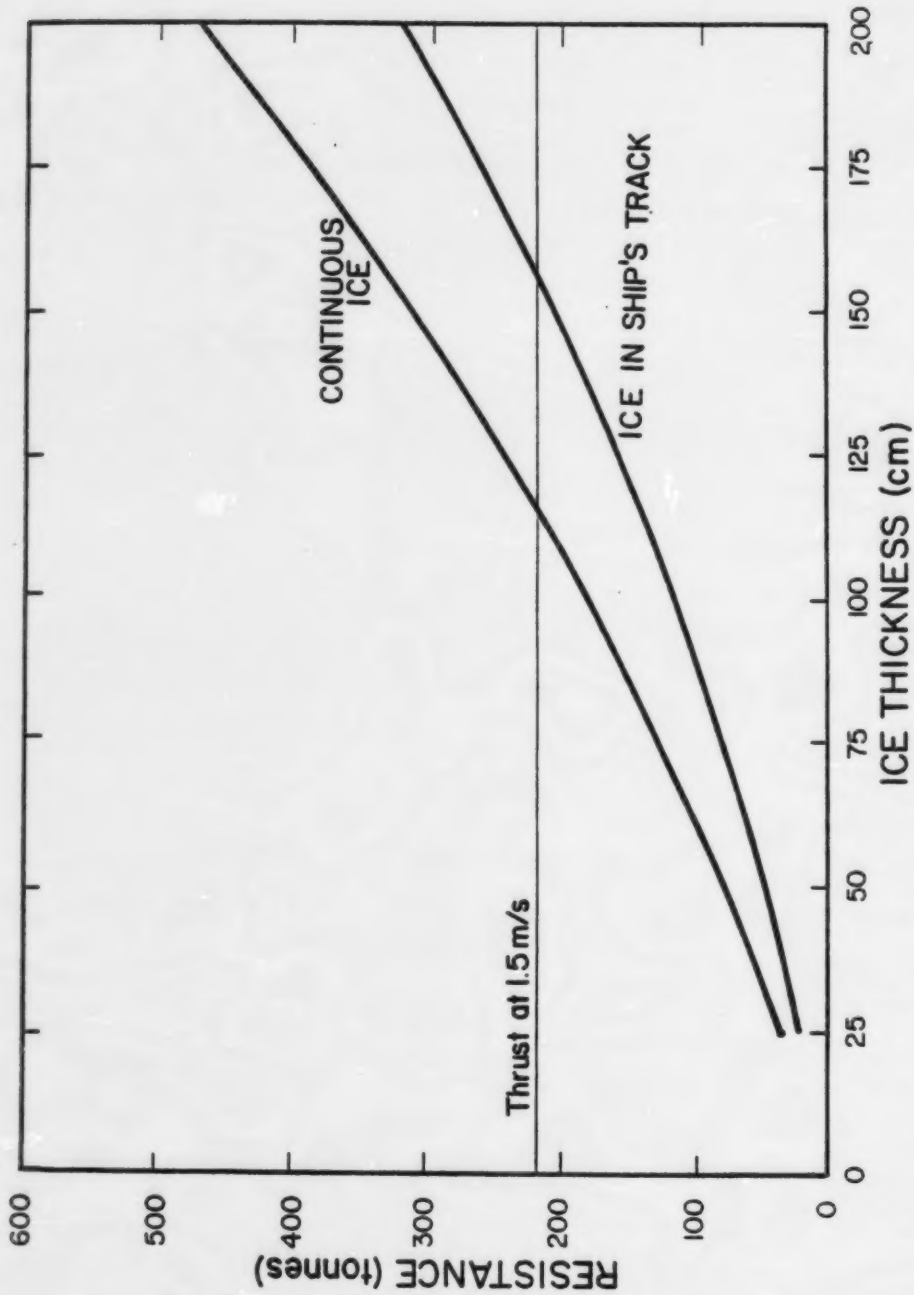


FIGURE 6.3 COMPARISON OF RESISTANCE IN CONTINUOUS ICE
& IN SHIP'S TRACK FOR "LOUIS ST. LAURENT"

assumptions about the mechanical properties of the ice in the ship's track, it has been determined that a ship with the capability of the LOUIS ST. LAURENT for example, would have to make only one track for a 15-day trip frequency as can be seen by combining Figures 6.1 and 6.3. A similar calculation for a frequency of 5 days resulted in a requirement for a second track to be made in early March.

6.4 Route Analysis

For the purposes of the transit time analysis, a single route into Groswater Bay and Lake Melville was selected. The ice conditions along this route as determined from the AES ice charts for 1969-79 were digitized and coded. These coded ice conditions were used as input in the ice resistance equations to determine transit times under various conditions. The route selected is shown in Figure 6.4 and is along the open water route recommended by the Sailing Directions for Labrador and Hudson Bay and follows a northern track along $54^{\circ}11'N$ latitude into Groswater Bay. This track has been extended to $52^{\circ}W$ longitude to encompass the pack ice in the study area. (A detailed description of the open water route is given in Appendix B.) It is noted here that variations of this route are often followed especially by mariners who are familiar with the area. Changes along this route may, of course, be necessary during ice conditions to avoid an area of significant resistance. While a large cargo ship may have some difficulty in "picking its way" among leads, it is expected that some manoeuvring of the ship will take place in the pack ice so that the ship can take advantage of these leads and other weak areas in the ice cover. This is not allowed for in the

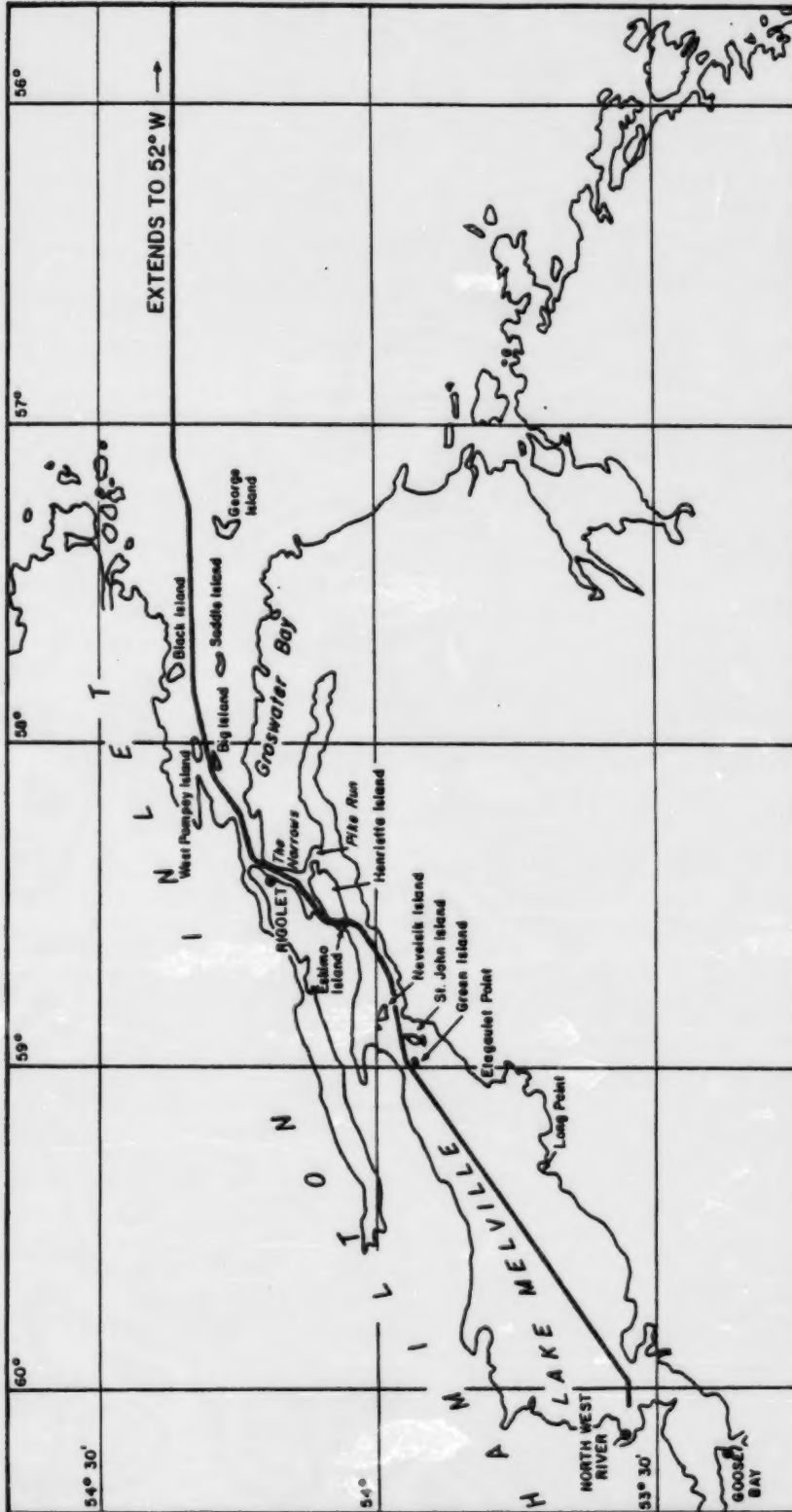


FIGURE 6.4 ROUTE USED FOR TRANSIT ANALYSIS

transit analysis, and as a result, some of the resulting transit times will be longer than would be actually experienced in a real operation. However, as mentioned earlier, these pessimistic times will tend to be offset by the neglect of ice pressure in the model. Delays due to such pressure may be fairly common and situations will arise in which the ship will not be able to make any headway and will simply have to wait until the pressure is relieved. In Lake Melville, the recommended route runs north of St. John and Green Islands, but in the description of the icebreaker probes in Section 2.3, it was seen that some ships followed a southerly route to avoid ridges along the recommended open water track. It is expected that such alternate routes will be common during the winter season.

While the track along $54^{\circ}11'N$ latitude was used to document the ice conditions according to the ice charts, a further analysis was carried out along a number of other possible routes through the pack ice and into Groswater Bay. In the absence of sufficient information about ice ridging, rafting, etc., and their distribution in the pack, the optimal route through the pack was selected principally on the basis of minimum distance through ice. It was considered that ice concentrations less than 6/10 did not present a significant impediment to navigation for the types of vessel under consideration in this study. Ice roses based on AES ice charts for the years 1969-79 were constructed to show the probability of encountering ice of concentration 6/10 and greater at various distances from the entrance to Groswater Bay. These concentrations were considered along lines running in six directions varying from 0° to

140° from the location (54°21'N, 56°45'W). The monthly ice roses as obtained from the ice charts for December through May are shown in Figures 6.5.1-6.5.6. The numbers found in each segment of each ray on the ice roses represent the probability of encountering ice of concentration 6/10 and greater in that segment in a normal year.

The variation of the extent of ice of 6/10 and greater concentration for the eleven years of data analysed is indicated by the numbers at the end of each ray on the ice roses. These numbers represent the maximum, average, and minimum extent in kilometers of ice of these concentrations for the period studied. The coverage of the charts did not extend beyond 300 kilometers to the north of Groswater Bay; therefore only an estimate of ice extent in that direction is possible.

South of Groswater Bay the edge of the Labrador ice pack normally extends a greater distance from the coast than it does further north, apparently being deflected eastward with the current along the protruding coastline. Consequently, when approaching Groswater Bay it is more advantageous to circumvent the southern part of the pack and to enter it where the smallest possible amount of ice intervenes between the position of the ship and Groswater Bay. This varies from day to day but in general it has been found that an approach through the pack from 30 to 60 degrees true (approximately NE) is most likely to encounter the minimum distance of ice to be transitted.

In December and January the extent of 6/10 and greater ice coverage may not reach as far south as Groswater Bay. When this is the case, a

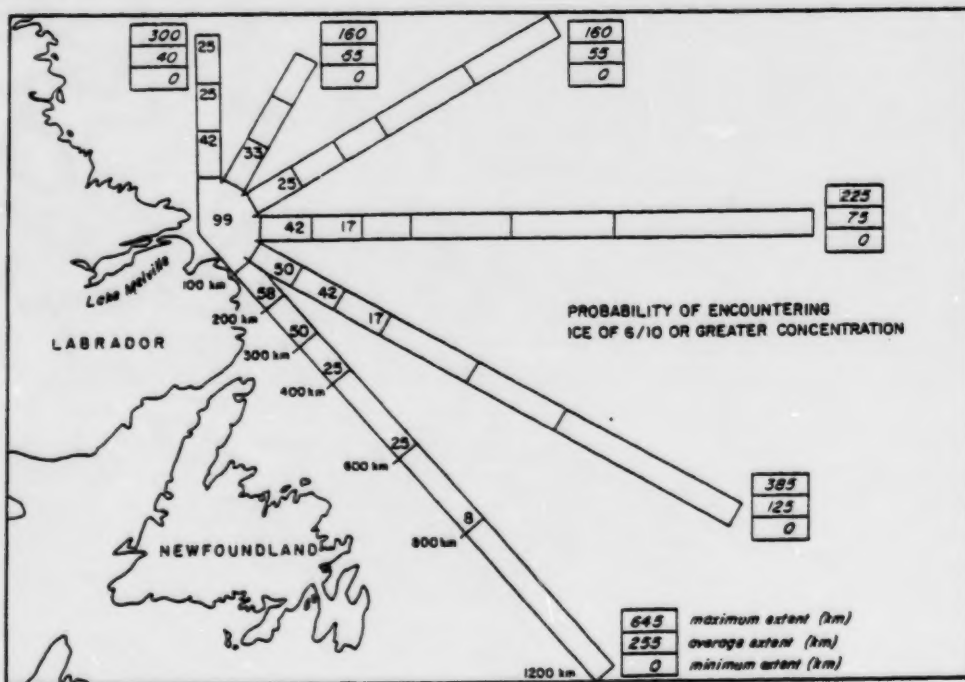


FIGURE 6.5.1 LABRADOR SEA "ICE ROSE" DECEMBER

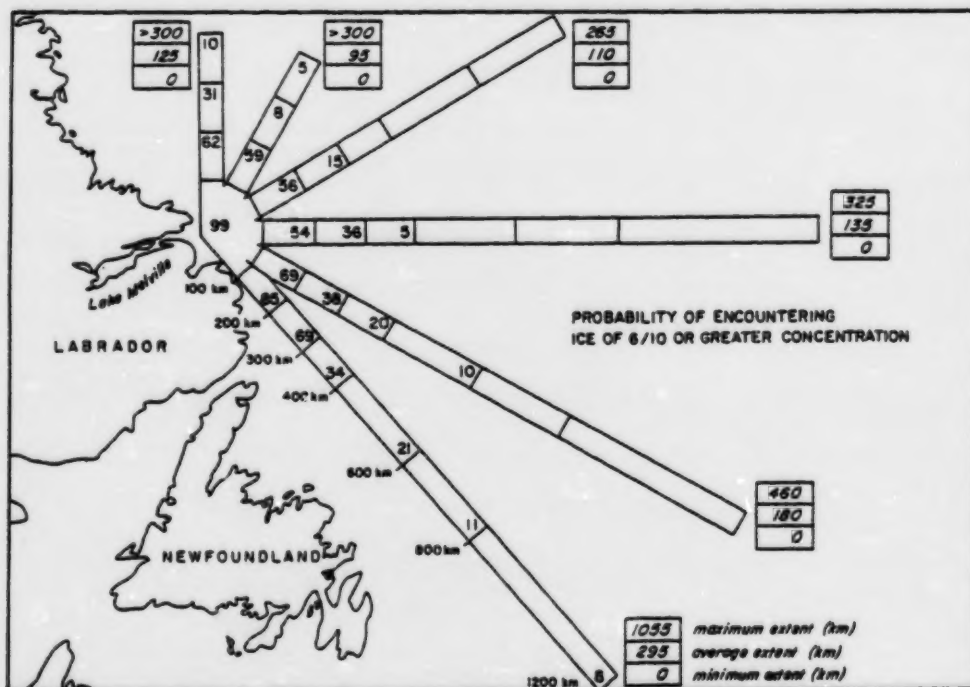
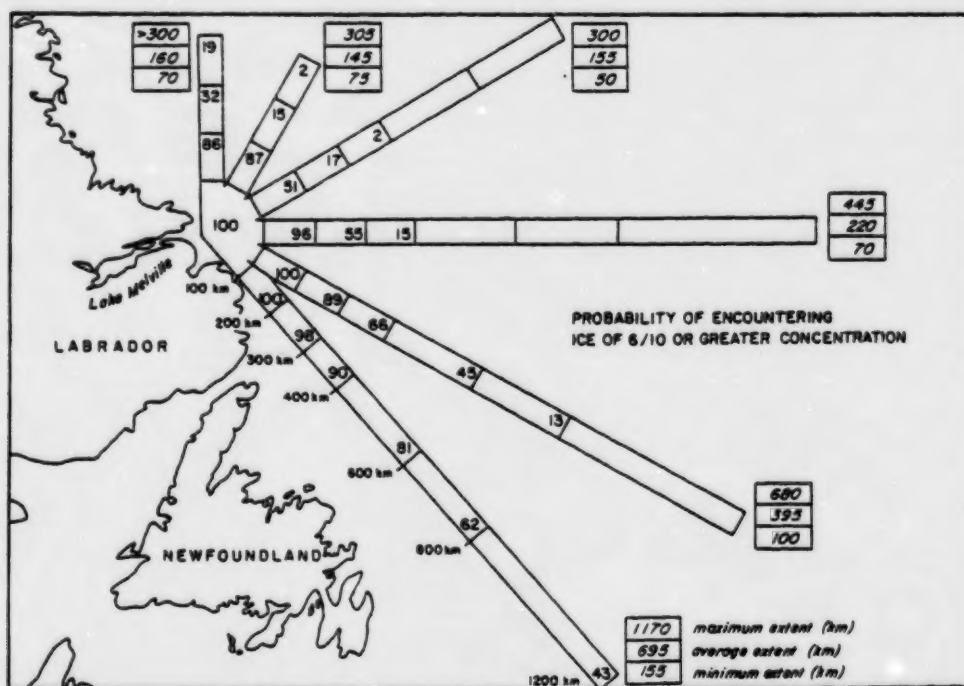
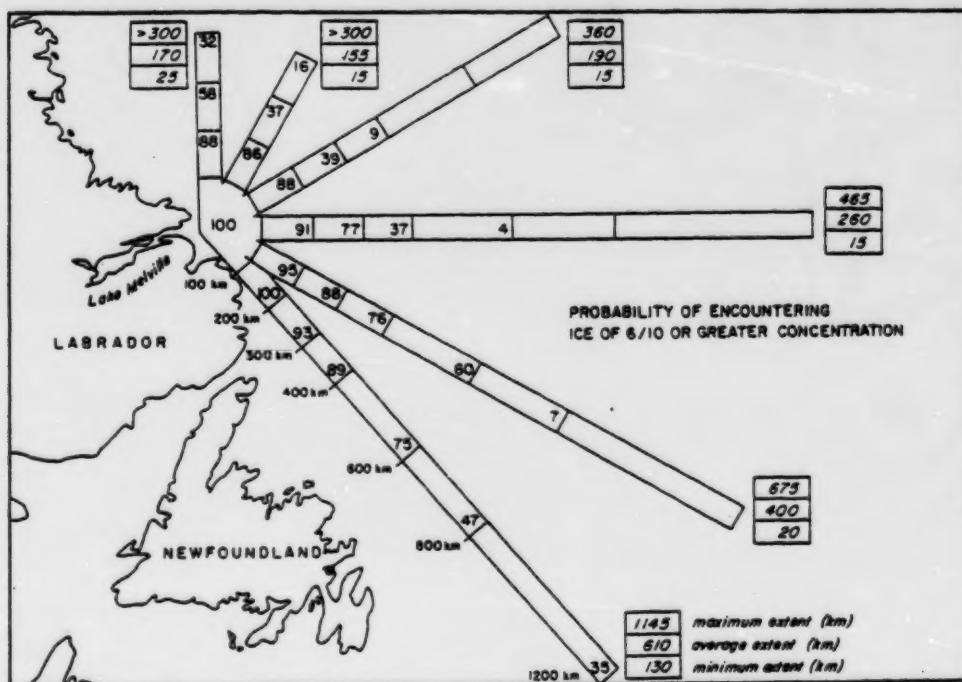


FIGURE 6.5.2 LABRADOR SEA "ICE ROSE" JANUARY



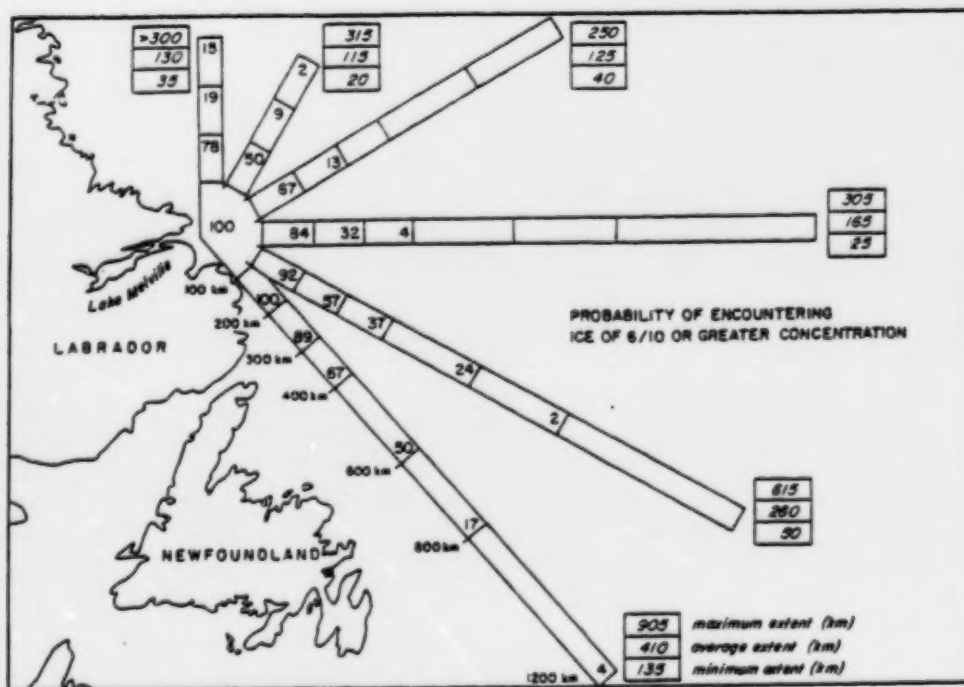


FIGURE 6.5.5 LABRADOR SEA "ICE ROSE" APRIL

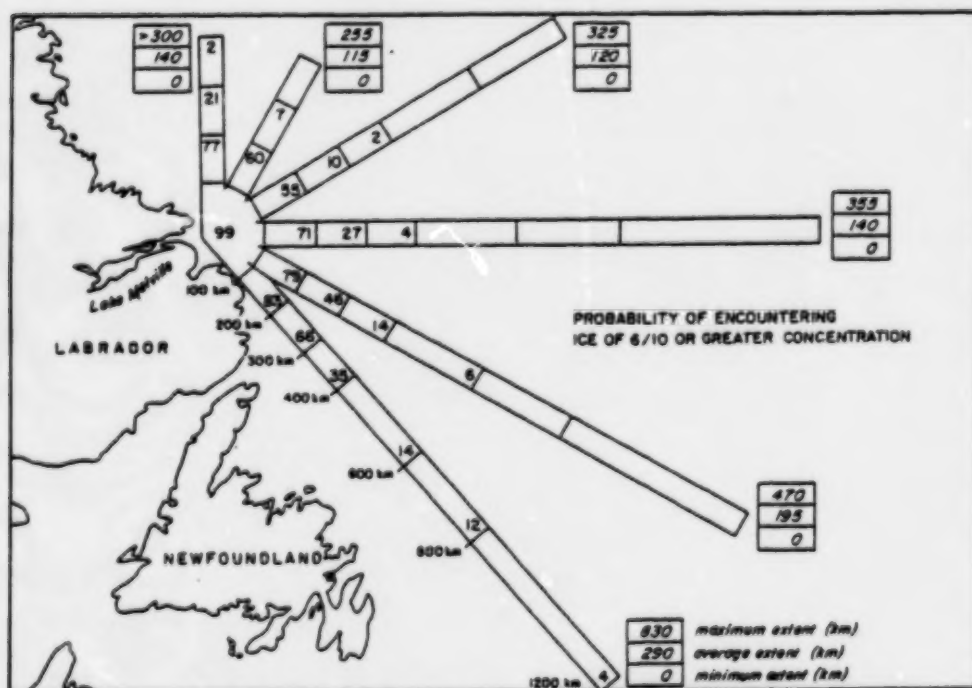


FIGURE 6.5.6 LABRADOR SEA "ICE ROSE" MAY

ship will of course proceed there by the most direct route. However, this situation occurs infrequently and the normal extent of ice of that concentration is approximately 55 km.

For the period from January to early May an approach from the 30 to 60 degrees true direction through the pack to Groswater Bay encounters on the average only about 130 km of ice of 6/10 and greater concentration compared to 180 to 205 km of ice normally found on a direct westerly approach. During these months, approaches from more southerly directions involve the passage through up to twice as much ice as from the northeasterly direction.

By late May, large areas of open water are found within the pack and along the coast south of Groswater Bay, and it may be faster to negotiate the most direct route through the pack rather than travel further north to take the route through the minimum expanse of ice.

6.5 Transit Simulation Results and Discussion

The transit model was run for three vessels, the icebreakers C.C.G.S. FRANKLIN and LOUIS ST. LAURENT and the icebreaking bulk-carrier M.V. ARCTIC. The appropriate ship parameters (see Appendix A) were then used in the various ice resistance formulas to determine the speed of the vessels under various ice conditions in the three modes of operation; viz, continuous movement in landfast ice or 10/10 pack ice, movement in pack ice of less than 10/10 concentration and movement in the ramming mode when ice conditions precluded continuous movement. It was determined

from this approach that in the continuous mode of operation, the ST. LAURENT could maintain about 1.5 m/sec in ice 1.3 m thick while the FRANKLIN and ARCTIC could maintain a similar speed in uniform ice thicknesses of just over 1.0 m and 0.85 m, respectively. The FRANKLIN has considerably less power than the ST. LAURENT and is also less powerful than the ARCTIC. However, the vessel design in terms of bow shape, draft, and power-to-displacement and power-to-length ratios allows it to move continuously in ice that is about 80 percent of the ST. LAURENT's capable ice thickness and about 120 percent of the ARCTIC's capable thickness in a continuous mode.

The environmental conditions used as input and the data handling procedure are described in Appendix A.

The average transit times as functions of time of year are shown in Figures 6.6, 6.7 and 6.8 for the LOUIS ST. LAURENT, the FRANKLIN and the M.V. ARCTIC, respectively. Histograms of the transit times for each ship are shown in Figures 6.9, 6.10 and 6.11. The total number of attempted passages in each case is 467 and is based on the number of Ice Central Charts used for environmental input. The transit times are calculated for each passage and averaged over two week periods from December 1 through July 31. The numbers of passages taking less than 10 days are shown, and it is only for these that the transit times are averaged. Each passage is assumed to begin at 54°11'N, 52°W and follow the route shown in Figure 6.4 to the western end of Lake Melville.

AVERAGE TRANSIT TIMES
"CCGS LOUIS ST. LAURENT"

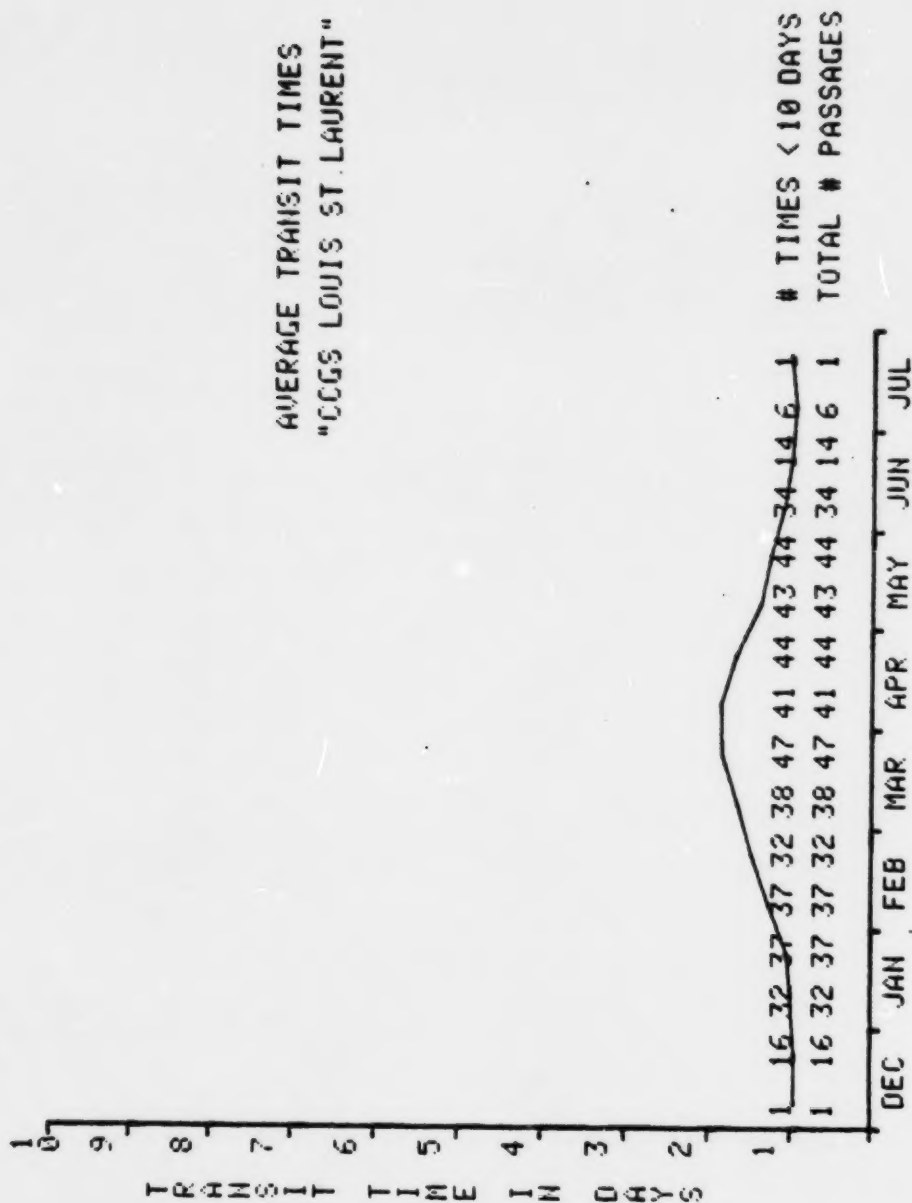


FIGURE 6.6

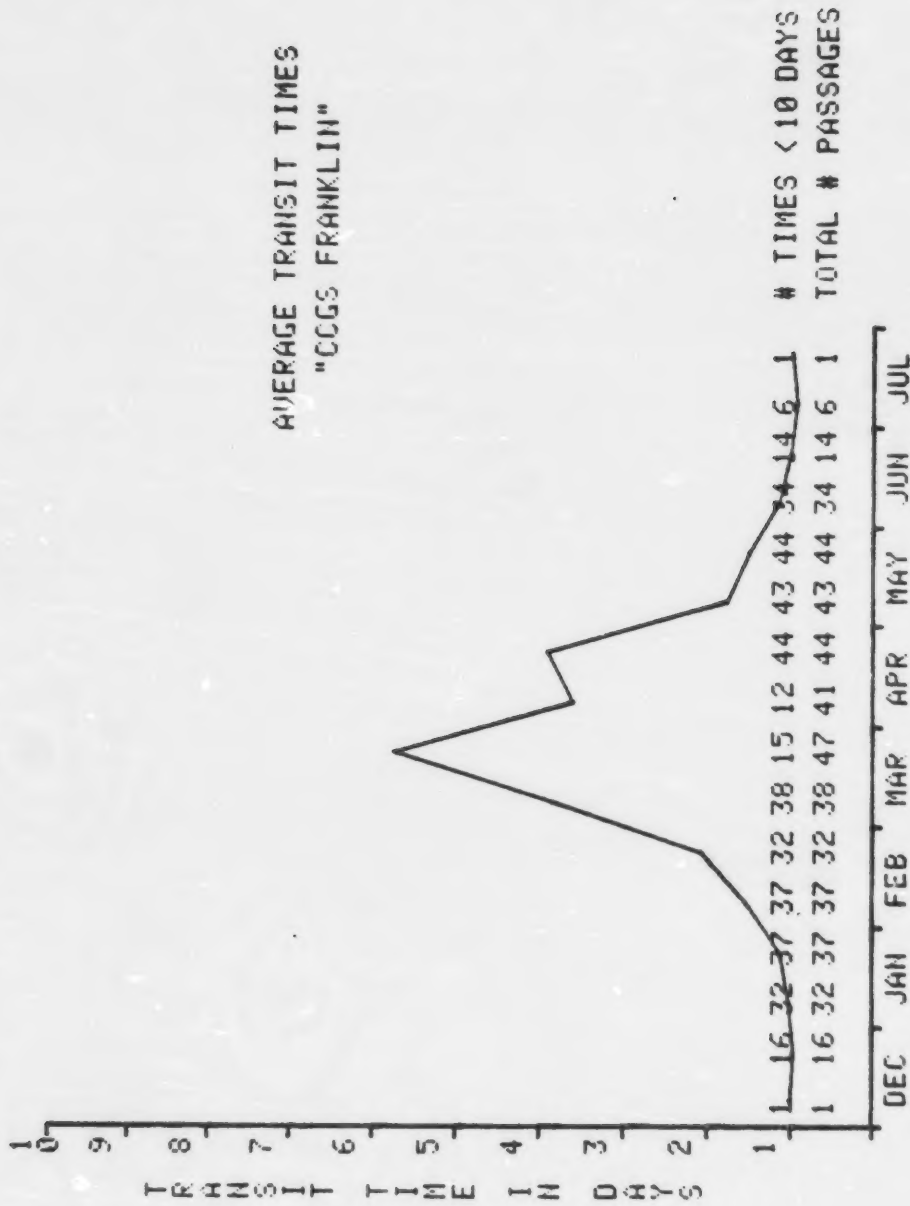


FIGURE 6.7

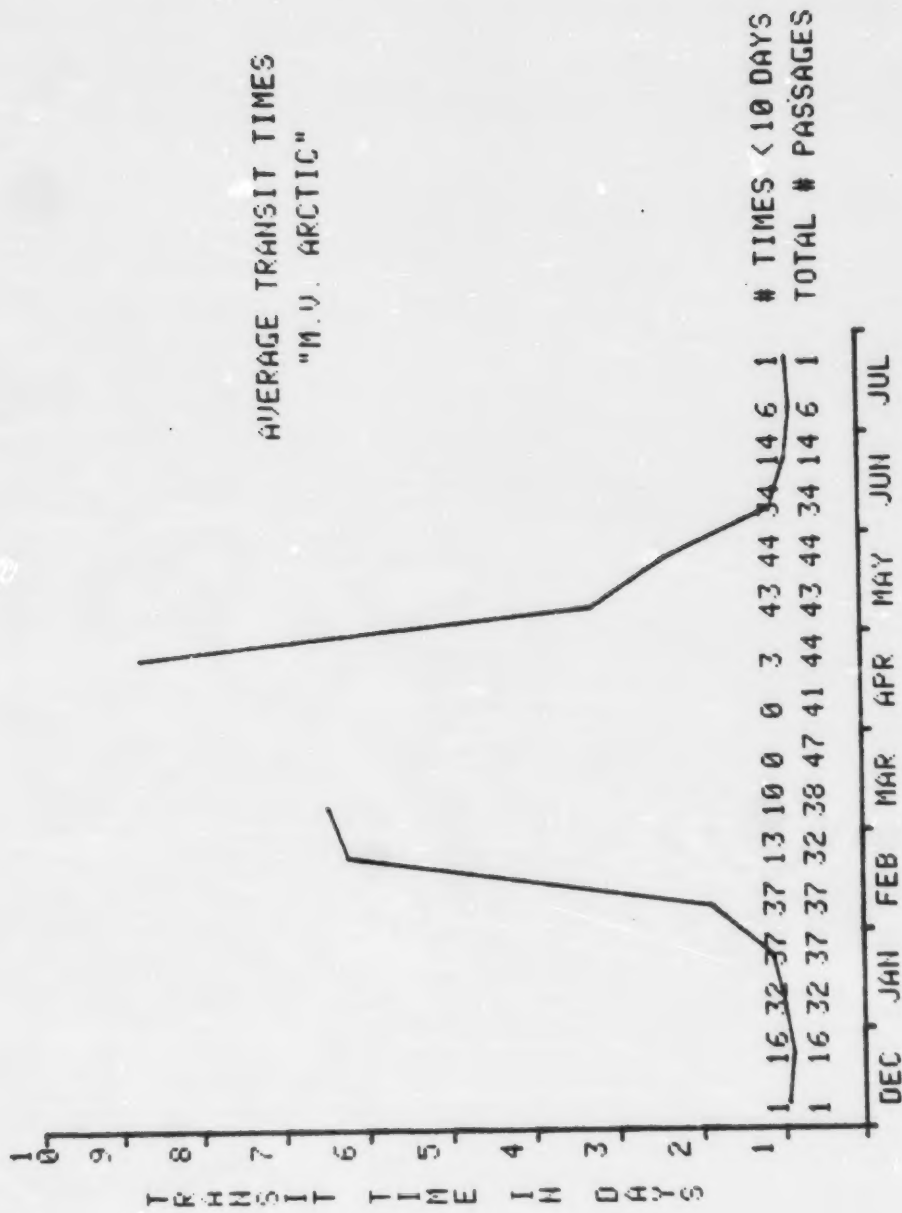


FIGURE 6.8

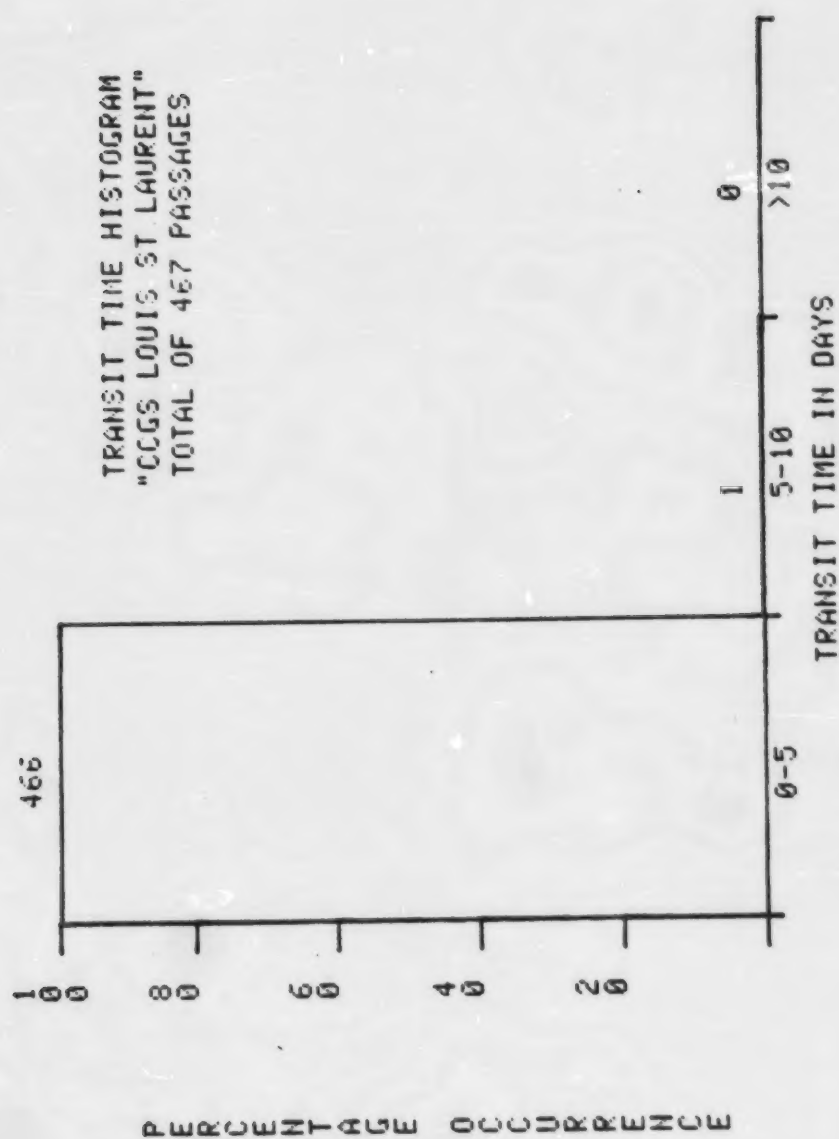


FIGURE 6.9

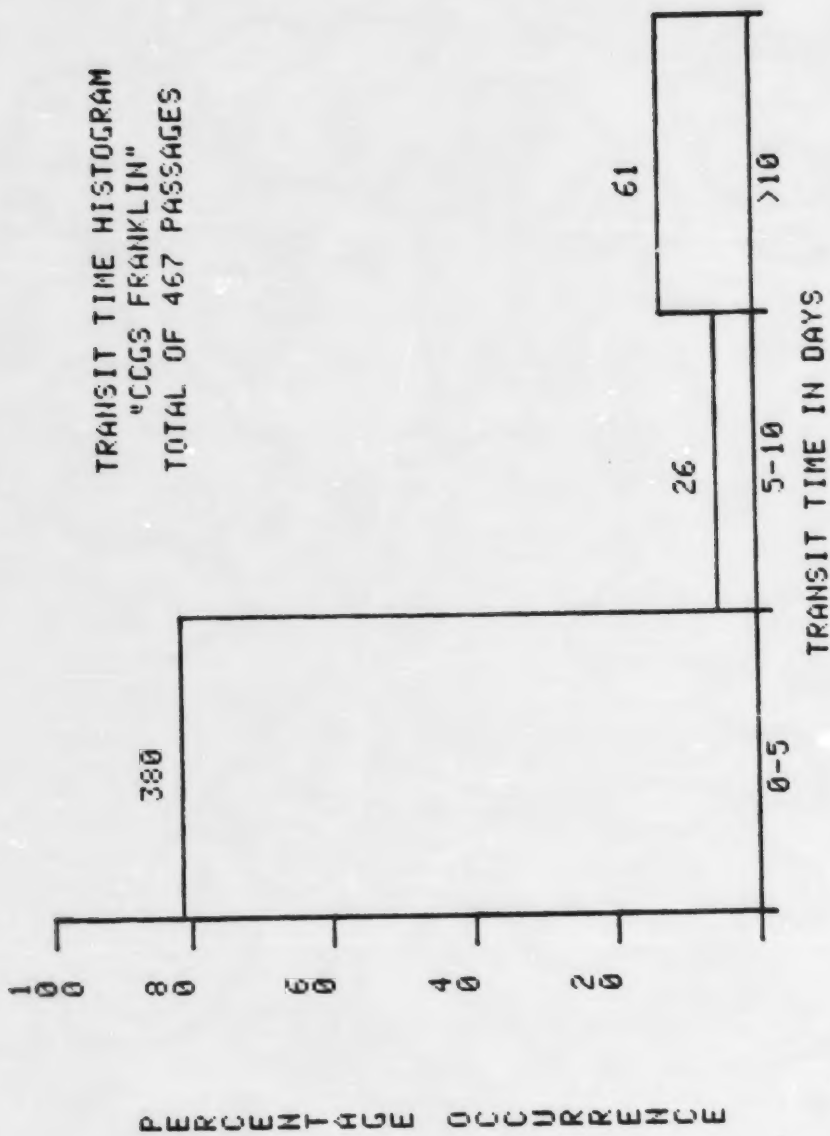


FIGURE 6.10

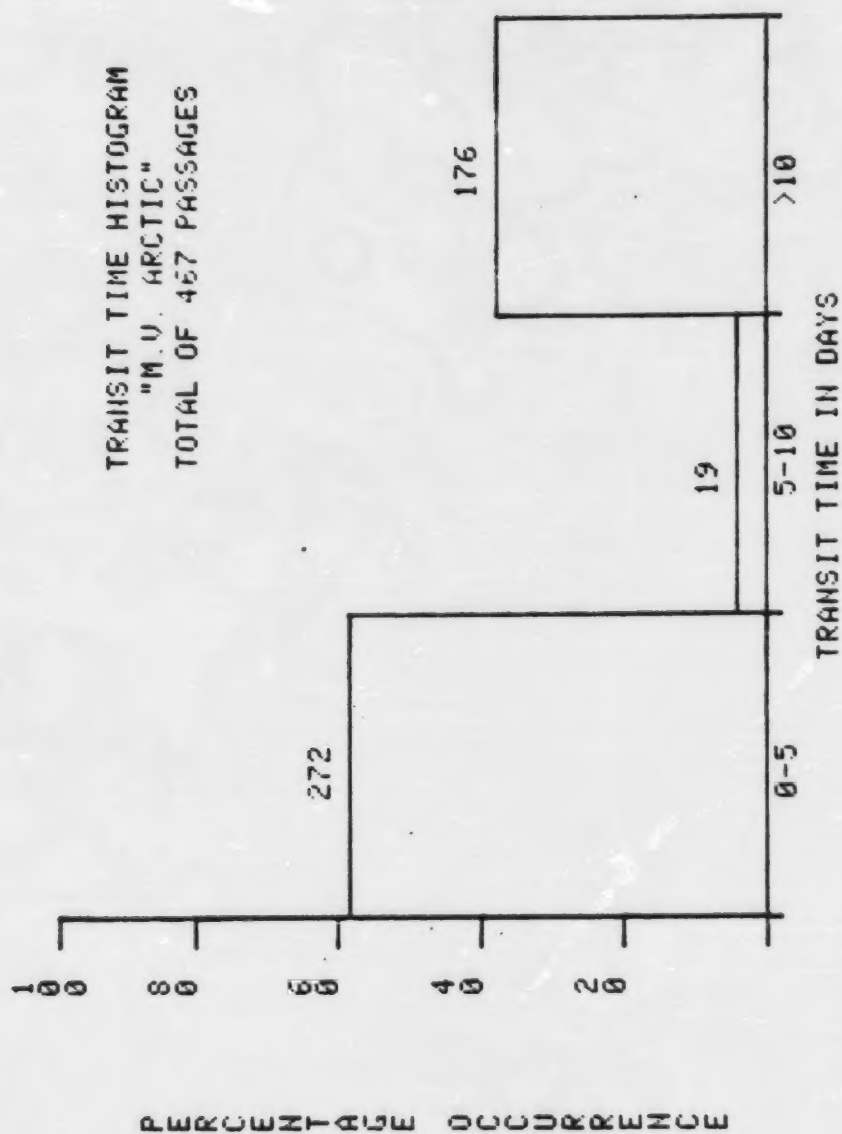


FIGURE 6.11

In each case, the transit time increased from December to early or mid-April and then decreased to the end of the season. The ST. LAURENT was successful in every attempt in reaching the western end of Lake Melville in a time of less than ten days. In fact, only one passage out of 467 took longer than five days. Even under the worst ice conditions during March and early April, the average transit time is only 2 days (compared with the open water transit time of approximately 3/4 day). The transit time greater than five days occurred in late March when the ice concentration in the pack was 10/10 for considerable distances and when ramming was often necessary to penetrate large areas of rough ice.

From Figure 6.7, it can be seen that the FRANKLIN experiences considerable delay during the last two weeks of March and the first two weeks of April when about 70% of the times are greater than 10 days. During this period, the resistance provided by the ice is often beyond the calculated continuous capability of the FRANKLIN, and it must resort to the ramming mode. From Figure 6.10, it is seen that 81 percent of all transits require less than 5 days while 6 and 13 percent of the transit times are 5-10 days and greater than 10 days respectively.

The results for the M.V. ARCTIC indicate that this ship would have severe problems in coping with ice conditions between the middle of February and early May. Almost 90 percent of all transit times during this period are greater than 10 days, and for the total number of passages considered, about 40 percent would involve transit times greater than 10 days as well. The ARCTIC, while being designed as a

Class 2 vessel, was found from the application of the ice resistance equations to be able to move continuously in ice of 0.85 m thickness and this thickness is exceeded in most parts of Lake Melville normally by mid-February. Beyond this thickness, the ARCTIC would be required to operate in the ramming mode which would cause the transit time to be increased significantly beyond the ten-day cut-off.

7. PRELIMINARY ECONOMIC ANALYSIS

7.1 Introduction

There is an economic penalty associated with vessel navigation in ice covered waters. The higher costs result from additional operating expenses due to delays and the extra wear and tear on a vessel operating in ice, the reduction in a vessel's overall cargo transport capability because voyages through ice covered waters generally take longer to complete, and the simple fact that an icebreaking or ice-strengthened vessel is more expensive in the first place than a normal one of the same transport capability.

A preliminary analysis was conducted to obtain an estimate of the additional cost associated with transport into and out of Lake Melville. Minimum or "break-even" freight rate was selected as a criterion to assess the effect of ice on vessel economics using complete open water navigation into Northwest Point as a datum.

7.2 Analysis

Minimum required freight rate (RFR) can be expressed as:

$$RFR = \frac{(CR)P + Y}{C} \quad (1)$$

where CR = capital recovery factor

P = initial capital investment

Y = sum of all operating expenses

C = cargo carrying capacity expressed as tons of load
carried per unit time

In the following analysis one trip per vessel will be costed. It will be assumed that the vessel is fully loaded and that operating costs comprise only ship costs (i.e., port, loading charges, etc. will not be taken into account).

Two voyages each using a different vessel are considered:

1. A 30,000 DWT carrier terminating at Northwest Point from an origin 2,400 n.m. away, corresponding roughly to a location in the Caribbean.
2. A 10,000 DWT carrier originating at Northwest Point with a destination 2,000 n.m. away corresponding roughly to a location in western Europe.

Both vessels will be assumed to have the same open water cruising speed of 9.3 m/s (18 kts).

Four operating expenses are considered each of which is assigned a cost increase factor for ice navigation. These are listed in Table 7.1 along with the factors which are applied only for the number of days operating in ice.

Only four cost centres were considered to keep the calculations simple and because fairly reliable numbers could be assigned to them.

After deciding upon values for the operating expenses, capital costs, etc., the calculation procedure was as follows:

TABLE 7.1
Operating Expenses for Ice Navigation
(from Nowacki et al., 1972)

<u>Cost Centre</u>	<u>Increase for Ice</u>
Fuel (F)	1.3
Wages (W)	1.2
Insurance (I)	1.2
Repair and Maintenance (R)	1.25

1. Determination of required freight rate for vessel under open water conditions, for entire voyage.
2. Determination of daily costs for that portion of voyage in ice using output of transit time prediction model, re-adjustment of daily costs as determined in (1), and calculation of an open water/ice freight rate. Re-adjustment of costs included the higher operating costs as indicated in Table 7.1 and a higher initial capital cost to account for ice strengthening.

The actual figures used in the calculations are shown in Table 7.2a and 7.2b and are based on data from Albery, Pullerits and Dickson (1978) and Nowacki et al. (1972). The calculated required freight rate is also shown in the tables. An average pack transit time of 1.9 days was determined using calculated values for the LOUIS ST. LAURENT, assuming that a cargo vessel strengthened to Class 2 follows the ST. LAURENT into and out of Lake Melville.

It is noted that for the small vessel a 47% increase in freight rate is calculated for ice capable operations. An increase of 54% is the corresponding figure for the larger ship. Admittedly the calculation method is a very approximate one and the results should be interpreted accordingly.

For the voyages analyzed, however, the overall result, a 50% increase in breakeven freight rate, indicates that there is sufficient justification to pursue a more in-depth economic feasibility analysis of cargo transport into and out of Lake Melville.

TABLE 7.2a
Required Freight Rate Calculation

Vessel: 10,000 DWT

	<u>Normal</u>	<u>Ice Strengthened, IB</u>
Capital	M\$9	M\$10.35
Capital Recovery Factor	0.15	0.15
Daily Capital Costs	\$3,700	\$4,280
Fuel/Day	\$3,500	\$3,844
Wages/Day	\$1,370	\$1,460
Insurance/Day	\$ 985	\$1,135
Maintenance/Day	\$ 495	\$ 990
Voyage Dist.	2,000 n.m.	2,000 n.m.
Voyage Time	4.6 days	5.8 days
Required Freight Rate	\$4.60/ton	\$6.75/ton

TABLE 7.2b
Required Freight Rate Calculation

Vessel: 30,000 DWT

	<u>Normal</u>	<u>Ice Strengthened</u>
Capital	M\$15	M\$17.25
Capital recovery factor	0.15	0.15
Daily Capital Cost	\$6,164	\$7,090
Fuel/Day	\$4,600	\$4,980
Wages/Day	\$2,055	\$3,107
Insurance/Day	\$1,640	\$1,975
Maintenance/Day	\$ 820	\$1,640
Voyage Distance	2,400 n.m.	2,400 n.m.
Voyage Time	5.5 days	6.9 days
Required Freight Rate	\$2.80/ton	\$4.30/ton

8. SUMMARY, CONCLUSIONS & RECOMMENDATIONS

This study has addressed the question of year-round navigation into Lake Melville, Labrador and has been concerned with documenting environmental conditions and obtaining a better understanding of the particular ice conditions which would affect year-round operations in the area. A field program carried out as a part of the study investigated ice conditions on Lake Melville in January, 1979 and also supported a remote sensing program in April, 1979. The primary intention of this field program was to investigate freeze-up conditions and to measure any large ridge formations that would be expected to present the greatest obstacles to navigation in the lake. Ridge formation in the narrow eastern section of the lake would be particularly significant since a ship would have less room to circumvent the formations. It was concluded from this field program that freeze-up during 1978 was not severe and that except for a number of small thermal ridges and some localized ridging in the eastern end of the lake near Green Island, the ice was not particularly rough.

A review of previous studies conducted in the area showed that the most substantial research into the ice conditions of Lake Melville was carried out by Memorial University of Newfoundland during the winters of 1972-73 and 1973-74. As it happened, the winter of 1972-73 produced unprecedented ice conditions on the lake and 1973-74, while being less extensive in heavy ice formations, also resulted in some major ridging conditions. An analysis of freeze-up conditions of Lake Melville for the winters of 1972-73 to 1978-79 from ship reports and on-ice surveys showed that heavy ridging can occur almost anywhere on the lake depending

on the meteorological conditions and the ice thickness during critical stages of freeze-up. It was found that ridging and rafting usually occur during heavy winds when the ice is in an unconsolidated state and is 0.15 - 0.30 m. thick.

Pack ice conditions have not been documented as well as the land-fast ice of Lake Melville, and there are some serious gaps in our knowledge of important pack ice features and parameters. In this study, all available reports were reviewed and, where possible, data from other sources such as ship reports, AES Ice Central charts and remotely sensed imagery were also used. The nature of the ice conditions as they would affect the movement and performance of ships operating in them was of primary concern, and particular attention was paid to such features as the frequency and orientation of leads and the frequency of multi-year ice and large ice formations. The Ice Central charts provide ice concentration and type but do not portray small areas of open water which would be of significance to the transit of conventional icebreakers since they are generally highly manoeuvrable. An analysis of SAR and SLAR imagery for the area concluded that leads are randomly oriented while a limited number of satellite photos did show large leads which tended to extend for considerable distances through the pack in an orientation essentially perpendicular to the direction of the ice movement. Either these leads did not exist during the periods of the SAR and SLAR overflights or the relatively narrow swath width of the sensors caused this feature to be missed. The satellite photos also showed that Groswater Bay often contains large areas of open water throughout winter and should thus allow for essentially routine navigation.

The frequency of occurrence of multi-year ice in the Labrador pack ice is not well known. However, multi-year ice is reported in the AES Ice Central charts, and it was determined from these charts that the ratio of multi-year to first year ice could be as high as eight percent late in the season.

Similarly, the frequency of occurrence and the severity of ice pressure are poorly documented for the study area, and further work is required to be able to quantify its effects on ship movement and to establish some relationship with the powering of vessels. The distribution and occurrence of heavy ice formations resulting from such pressure also require considerable study.

A review of ice navigation experiences in other areas was carried out, and some extrapolations were made to the study area. A major study on year-round navigation in the Great Lakes concluded that winter operations are feasible with the support of ice breakers capable of breaking up to 1 m of landfast, freshwater ice. Winter navigation in the northern parts of the Baltic Sea is now routine with the aid of icebreakers with 16.2 Mw (22,000 hp) of power. Ice in the most northerly portions of this area grows to 1 m in thickness, and there is often extensive ridging in the central part of the Gulf of Bothnia. Because of the similarity in ice conditions in this and the study area, it is suggested that ships of somewhat similar capability would be required for effective year-round operation in Lake Melville.

The experiences of a number of local operators and navigators in the study area during the regular navigation season were addressed, and the log books of a number of ships were reviewed especially with regard to voyages undertaken late in the season during freeze-up. Information from these ships was used in the analysis of freeze-up patterns on Lake Melville.

Several icebreaker probes and normal icebreaker operations have taken place in the study area in the past ten to fifteen years. Of the documented voyages into Lake Melville, it was seen that on several occasions, the vessels reached the eastern end of the lake but found the ice to be too thick to proceed further west. The successful voyages were either in early winter or late spring, the majority of these involving the CCGS JOHN A. MACDONALD. It was concluded that on the basis of the performance of the MACDONALD, the season could be extended 1 - 1 1/2 months beyond the last of November using a vessel of similar capability. Likewise, the season could be opened in spring a few weeks earlier than usual using a similar vessel.

A major part of the present study involved the development of a computer model to predict transit times of vessels in the study area from freeze-up to breakup. The model, which is based on ice resistance and icebreaking theories, used the AES Ice Central charts as the primary source of ice data. These charts, which are the only substantial data file on ice conditions in the study area, were digitized and the information was incorporated into the computer model to determine the transit times of three Canadian icebreaking ships from freeze-up to breakup at two-

week intervals. Because the ice charts do not report small leads which a conventional icebreaker could use to advantage, the computed transit times for these ships are probably greater than would actually be the case. This, however, does not necessarily apply to a large cargo ship which would not have the same degree of manoeuvrability as a conventional icebreaker and would tend to follow a "straightline" course. In addition, the effect of sea ice pressure is not incorporated directly into the model; thus, in this case the computed times would tend to be less than the actual times. It has been suggested that due to various combinations of wind and current, delays due to pressure of greater than fifteen percent could be expected in general during the heavy ice months.

In order to predict the performances of ships moving in ice, it is clearly necessary to have a good understanding of the various ice parameters which enter into the ice resistance equations. The most important of these is ice thickness, and it has been seen that this parameter has not been well documented in the study area. Likewise, there is a scarcity of data on ice floe size, the flexural strength of uniform ice and the crushing strength of ridges.

The transit model was applied to the Canadian Coast Guard icebreakers LOUIS ST. LAURENT and FRANKLIN and the Canadian icebreaking cargo ship MV ARCTIC. It was determined that the ST. LAURENT could travel through the pack ice and the ice in Lake Melville along a specific route in less than five days in virtually all cases studied. The FRANKLIN experiences considerable delay during late March and early April when seventy percent of the voyages considered took longer than ten days.

However, over eighty percent of the total voyages of the FRANKLIN over the entire ice season are accomplished in less than five days. The MV ARCTIC was found to experience severe delays between mid February and early May when almost ninety percent of all voyages during this period took longer than ten days. Based on the results of this theoretical investigation and on the experience of operators in ice conditions in other areas, it is suggested that an icebreaking vessel in the order of 15 Mw (20,000 hp) would be required for efficient year-round operation in the study area.

In view of the limited knowledge of ice conditions in the study area, especially the pack ice, a long-term program in the order of five winter seasons is required to provide more information on the basic ice features and parameters. Emphasis should be placed on collecting data on the following:

- (i) ice thickness
- (ii) floe sizes
- (iii) occurrence and severity of sea ice pressure
- (iv) occurrence and characteristics of ridges, multiyear floes, hummocks, etc.
- (v) occurrence and orientation of navigable leads
- (vi) snow cover.

In the short term, a pilot study should be undertaken to investigate the performance of an icebreaker through the pack and Lake Melville. From the results of the present study, it is recommended that a vessel equivalent to a class 3 icebreaker be used for programs carried out prior to March and a class 4 icebreaker for a March or April program.

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Finally, an extensive economic analysis is recommended to determine costs for both icebreaker cargo ships and ice strengthened cargo ships requiring icebreaker support.

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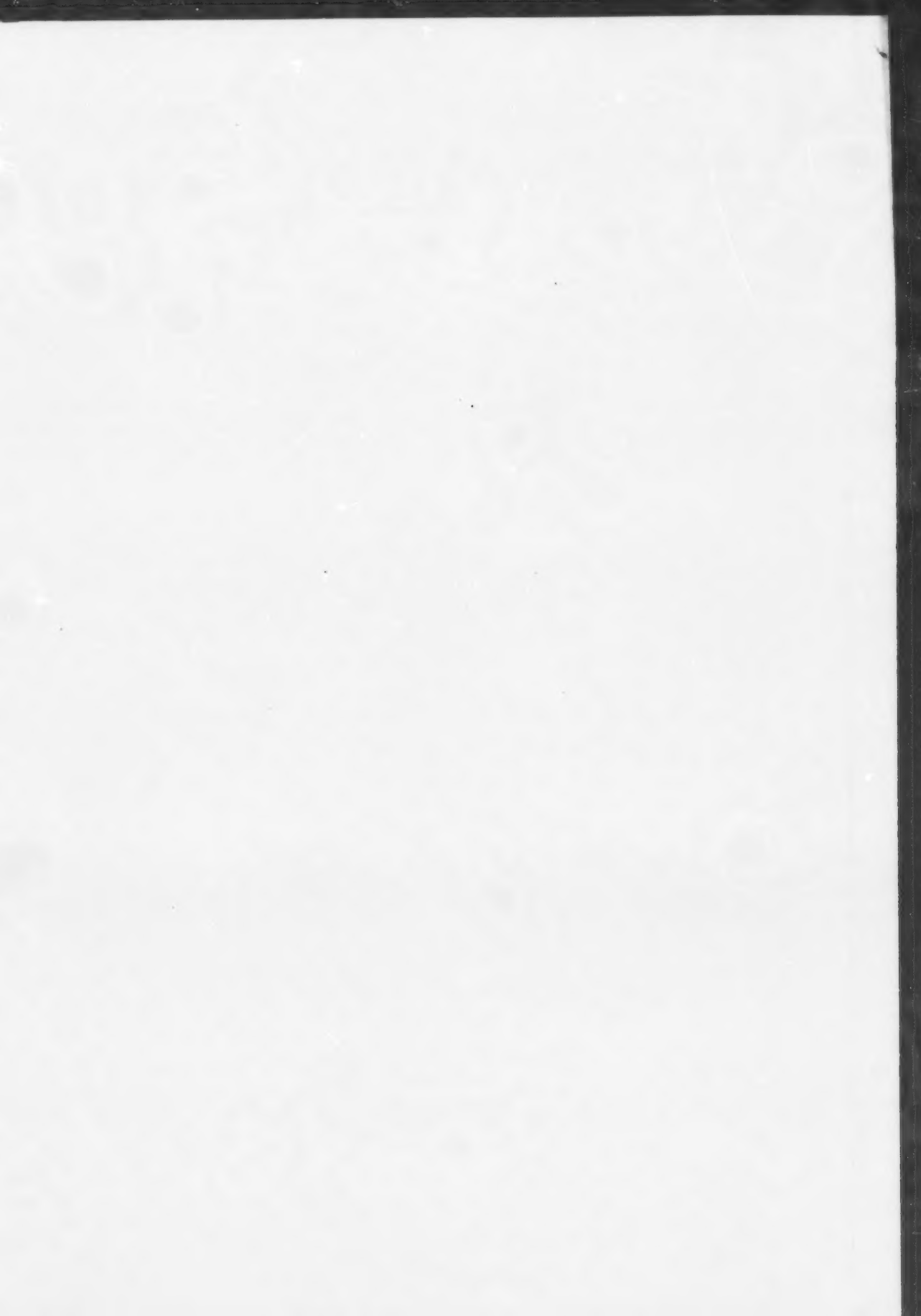
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LAKE MELVILLE/OFFSHORE LABRADOR YEAR-ROUND

NAVIGATION STUDY, 1978-79

APPENDIX A

ICE RESISTANCE THEORIES AND TRANSIT MODEL DEVELOPMENT

DESCRIPTION AND APPLICATION

LIST OF SYMBOLS

- K_i = Numerical value from model experiments (Kashteljan eqn.)
- B = Ship beam (m)
- σ = ice flexural strength (MPa)
- h = ice thickness (m)
- μ_0 = efficiency factor = $1 + \frac{\Sigma_{111}}{1 + \Sigma_{11}}$ (Kashteljan eqn.)
- Σ_{111} = Total horizontal stress (Pa) (Kashteljan eqn.)
- Σ_{11} = Total vertical stress applied on the ice by the front part of the ship (Pa) (Kashteljan eqn.)
- K_2', K_2'' = Factors which take into account all assumptions and inaccuracies allowed in Kashteljan eqn.
- C_0 = A constant (Kashteljan eqn.)
- E = modulus of elasticity of ice
- V = ship velocity m/sec.
- x, y = constants from model experiments (Kashteljan eqn.)
- η_2 = the ice cutting coefficient which takes into account hull shape $\eta_2 = \frac{1}{\Sigma_{111}}$ (Kashteljan eqn.)
- K_3 = a factor which takes into account all assumptions and inaccuracies allowed in the derivation of Kashteljan eqn. for flow resistance
- g = Acceleration due to gravity
- sc = snow cover thickness (ft, Lewis & Edwards equation)
- C_B = ship block coefficient
- H = ship draft (m)
- μ = coefficient of friction
- C_1 = constant, form dependent taken as 11.75 (Bustard eqn.)
- C_2 = constant, form dependent, taken as 0.17 (Bustard eqn.)

- L = ship length (m)
- n = exponent, taken as 1.5 (Bustard eqn.)
- shp = shaft horsepower
- C'_0 = constant dependent on hull form, taken as 0.23 (Kloppenburger eqn.)
- C'_1 = constant dependent on hull form, taken as 8.6 (Kloppenburger eqn.)
- C'_2 = constant dependent on hull form, taken as 1.7 (Kloppenburger eqn.)
- C''_0, C''_1, C''_2 = constants (Mathews eqn.)
- C_s, C_B, C_v = hull form coefficients (Vance eqn.)
- σ_F = flexure strength of ice (MPa)
- ρ_w = density of water
- ρ_i = density of ice
- ρ_Δ = density difference of water and ice
- α = half angle of entrance of a waterline (Enkvist eqn.)
- β = angle between low transverse section and vertical plane (Enkvist eqn.)
- ϕ = angle between stem and horizontal plane (Enkvist eqn.)
- ψ = angle between a horizontal plane and a section perpendicular to waterline (Enkvist eqn.)
- $\bar{s}$ = depth of submersion (m) (Enkvist eqn.)
- A_{WLF} = area of waterplane of entrance (Enkvist eqn.)
- H_{BW} = height of bow wave (Enkvist eqn.)

A.1 THEORIES OF SHIP RESISTANCE IN ICE COVERED WATERS

Introduction

The nature and magnitude of the resistance experienced by a vessel attempting to make headway in ice covered water depends both upon the character and properties of the ice and characteristics of the particular vessel. In general, four kinds of resistance due to various ice regimes have been noted:

1. Resistance due to continuous breaking of the ice in a more or less uniform field;
2. Variable but continuous resistance in a field comprising separate but closely packed floes having variable properties, particularly thickness;
3. Discontinuous resistance in a field whose passage requires ramming, characteristic of a severely ridged and/or very thick ice regime;
4. Open water resistance, which is increased in an unconsolidated ice field due to the manoeuvring required when seeking out leads.

In this section, the work of various investigators on the prediction of ship resistance due to ice is surveyed. An examination is made of the applicability of the theoretical knowledge to the practical problems of transiting the regimes discussed above, particularly in relation to the ship transit time computer model development.

A.1.1 Continuous Ice Breaking

This mode of advance takes place ideally in fields in which the ice properties exhibit spatial homogeneity and the cover is of a uniform thickness. The rate of advance depends on the hull shape and available power of the ship and on the ice thickness. For a given vessel, continuous advance will cease when a particular ice thickness is exceeded.

The earliest work attempting to predict ship resistance in ice (Runeberg, 1889) related the resistance to only one parameter, the force necessary for fracturing the ice. Later efforts recognized that resistance could be comprised of several components including ice fracture, inertia, friction between vessel and ice and gravity due to the uplifting and submerging of the broken ice. However, various investigators arrived at different conclusions regarding the relative contribution of each component to total resistance. This apparently is due to the lack of consistent theoretical and experimental approaches to the problem.

In the following sections, some analytical and semi-empirical models which have been used by ship designers in recent years are discussed.

Kashteljan et al. (1968)

Kashteljan et al. published an ice resistance equation based on extensive theoretical and experimental work. The following assumptions were made:

1. Total resistance is made up of velocity dependent and so-

called direct components which are independent of each other;

2. Icebreaker advance speed is constant.

The equation for the total resistance has the form:

$$R_T = R_1 + R_2 + R_3 + R_4 \quad (1)$$

where

R_T = total resistance

R_1 = resistance due to fracture

$$R_1 = K_1 B \sigma h \mu_0 \quad (2)$$

R_2 = resistance due to gravity

$$\begin{aligned} R_2 = & K_2' C_0 h^{1.75} \sigma^{1.25} \mu_0 \\ & + K_2'' \rho_i B h^{1.75} E^{0.25} \mu_0 \\ & + K_2''' \rho_i B h^2 \mu_0 \end{aligned}$$

R_3 = velocity dependent resistance due to penetration
through broken ice

$$R_3 = K_3 B^x h v^y (1/\eta_2) \quad (4)$$

R_4 = open water resistance

Based on model and full scale tests using the Russian icebreaker ERMAK, these investigators arrived at values for the empirical constants and concluded that the first term in the gravity resistance formula, R_2 , is important. The final equation became:

$$R_T = 0.004 B \sigma h \mu_0 + 3.5 \rho_i B h^2 \mu_0 + 0.25 B^{1.65} \frac{h v}{\eta_2} \quad (5)$$

Lewis and Edwards (1970)

Based on a series of full scale and model tests these researchers derived the following dimensionless equations which are generally limited to the ships tested:

i) Full scale data

$$\frac{R}{\rho_w g B h^2} = 5.259 + 4.35 \frac{V}{\sqrt{gh}} + 1.676 \frac{V^2}{gh} + 5.464 \frac{Sc}{h} \quad (6)$$

ii) Model tests

$$\frac{R}{\rho_w g B h^2} = 3.455 + 0.019 \frac{\sigma}{\rho_w g h} + 4.680 \frac{V}{\sqrt{gh}} \quad (7)$$

Milano (1973)

Milano discusses an extremely lengthy derivation based strictly upon theoretical considerations. The product of this analysis is a computer program incorporating 22 ship parameters and 10 environmental constants. His approach generated considerable controversy, and the method is generally considered to give pessimistic results.

Bustard (1972)

Bustard developed an equation to show the effect of ship size on the required horsepower for icebreaking. The equation is of the form

$$SHP = B h^2 [C_1 + C_2 \frac{(100V)^n}{\sqrt{L}}] \quad (8)$$

Kloppenburger (1975)

Based on model tests in the Hamburg ship model basin, Kloppenburger

proposed the following form of ice resistance:

$$R = C_0' \sigma h^2 + C_1' \rho_w g B h^2 + C_2' \rho_w B h v^2 \quad (2)$$

Mathews (1975)

Mathews presented a general equation for estimating ship resistance in ice based on work by Lewis and Edwards (1970) and others. The equation is of the form:

$$\frac{R}{\rho_w g B h^2} = C_0'' + C_1'' \sigma^1 + C_2'' F^2 \quad (10)$$

where $\sigma^1 = \sigma / \rho_w g h$ and $F = v / \sqrt{g h}$

Vance (1975)

Based on an analysis of existing icebreakers, Vance developed the following equations to estimate ship resistance:

$$R = C_s \rho_\Delta g B h^2 + C_B \sigma_f B h + C_v \rho_i v^2 L h^{0.65} B^{0.35} \quad (11)$$

Enkvist (1972)

Based on theoretical analysis, experimental investigation of model data and full scale data, Enkvist developed an equation representing ice resistance. This formula divides the total resistance into three components, namely resistance due to breaking of ice, resistance due to submersion of ice and velocity dependent resistance. The equation is as follows:

$$\begin{aligned} R = & \frac{C \sigma B h \sigma}{E} (1 + \eta_{\mu_s} \eta_{\mu_c}) + V^2 B \tan^2(\phi) \rho_i (h + 0.218 l) (1 + \eta_{\mu_s} \eta_{\mu_c}) \\ & + B l g \rho_w (0.167 l \sin \psi + 0.5 H_{BW}) \frac{(\eta_{\mu\psi} + \eta_{n\theta})}{2} \\ & + g \rho_\Delta B h H (\eta_{sp} + \mu \eta_{s\mu} E \frac{L_E}{H}) \end{aligned} \quad (12)$$

$$\text{where } \eta_{\mu s} = \frac{1}{\sin \phi \cos \phi}$$

$$\eta_{s\mu E} = A \frac{\sin B}{\frac{WLF}{BL_E}}$$

$$\eta_{\mu c} = \frac{\mu}{1 - \mu \frac{\sin \phi}{60\psi}}$$

$$l = 5h$$

$$L_E = 0.2L$$

$$\eta_{\mu \psi} = \frac{\sin \phi \cos \psi + \mu \cos^2 \phi}{\cos \psi \cos \phi - \mu \sin \phi \cos \phi}$$

$$\eta_{\mu \phi} = \frac{\tan \phi + \mu}{1 - \mu \tan \phi}$$

$$\eta_{\mu \phi} = \frac{\sin \psi \sin \alpha}{\mu \cos \alpha}$$

$$\eta_{sp} = \frac{\sum}{\prod}$$

Johansson (1977)

Johansson developed an empirical formula to estimate ship resistance in a continuous mode of icebreaking. The ice resistance formula was as follows:

$$R = 1.7 \times h^{1.5} \times B(2 - 0.0325 \phi + 0.00275 \phi^2) \times (1 - C_{AB} + 0.282 V^{1.2}) \quad (13)$$

This formula was used by the Winter Navigation Research Board in Finland and Sweden. It takes the effect of air bubbling into account (coefficient C_{AB}).

Comments on Different Methods

From the foregoing it is evident that there is a wide choice of predictive icebreaking resistance equations; however, the majority of these methods are limited to the class, type (cargo, icebreaker, etc.)

and size of ships under study. Extreme care must be taken in extrapolating the results obtained to new ship designs.

A modified form of Enkvist's equation has been selected for use in the transit model for this study. The equation is "less empirical" than others and contains several ship and ice parameters, which allows application to a variety of ship designs and ice conditions. The modification was performed in order to make Enkvist's equation "less optimistic" and to have it agree more closely with observed resistance measurements on selected ships. The resulting equation is:

$$R = C \frac{\sigma}{E} B(2h) \sigma (1 + \eta_{us} \eta_{uc}) + V^2 B \tan^2 \phi \rho_i (2h + 0.218l) (1 + \eta_{us} \eta_{uc}) \\ + B l g \rho_w (0.167 l \sin \psi + 0.5 H_{BW}) \frac{(\eta_{up} + \eta_{ue})}{2} \\ + g \rho_{\Delta} B(2h) H (\eta_{sp} + \mu \eta_{su} E \frac{L_E}{H})$$

A.1.2 Ice Floe Resistance

Introduction

The resistance to moving through an ice floe field is different from continuous ice breaking resistance since the ship has to push ice floes aside rather than break them. Developing an expression for estimating ship resistance in an ice floe field presents difficulties because of the complexity of the interaction between the ship and the floes. This problem is compounded when the ice concentration, floe size and ice strength change along the ship route. Some attempts have been made to formulate ice floe resistance expressions based on theoretical impact theories and/or full scale and model measurements. The more familiar theories are discussed below.

Review of Existing Experience

Popov et al. (1968) calculated the ice impact loads on an ice-breaker hull and later improved his expression by considering the reflecting impacts. Major et al. (1975) have formed a model, based on Popov's expression, to predict hull ice impact loads with special reference to ships navigating in the St. Lawrence River. Milano (1973) derived an expression for estimating ice floe forces on a ship's hull. He concluded that ice concentrations less than 6/10 or 7/10 do not represent a significant obstacle to a ship's motion.

Buzuev and Ryvlin (1966) developed an empirical relationship, based on laboratory and field investigations, to calculate the magnitude of ice resistance under different ice conditions. The relationship was used to produce curves of resistance as a function of ship speed and ice floe thickness. The resistance curves were approximated by the relationship:

$$R_{ir} = h^{1.2} (c + 9.0 v^{1.3}) \quad (14)$$

where c is an empirical coefficient.

Kashteljan et al. (1968) have developed a modified form of equation (14) as well as curves indicating the value of the coefficient c for different floe diameters. The modified equation is:

$$R = 3.77 (10B) h^{1.2} (c + 9 v^{1.3}) \quad (15)$$

where B = beam of ship (m)

c = 6.25 for 30 m floes

= 55.5 for 500 m floes

Bronnikov (1959) developed an expression to calculate ship resistance in an ice floe field. This expression is based on full scale tests on a Russian standard Arctic cargo ship, and the expression itself is an interpolation of the measured resistance to account for ships differing from the standard Russian ship.

$$R_{ip} = (R_{ip})_0 \left(\frac{\Delta}{\Delta_0} \right)^s \left(\frac{h}{h_0} \right)^m \left(\frac{s}{s_0} \right)^n \left(\frac{H}{H_0} \right)^p \left(\frac{[L/B]_0}{[L/B]} \right)^q \left(\frac{C_{B0}}{C_B} \right)^r \left(\frac{[B_1/B]_0}{[B_1/B]} \right)^k \quad (16)$$

The subscript zero denotes the standard Arctic Russian cargo ship that was tested by Bronnikov and the quantities without subscripts represent the other ships tested in comparison. R_{ip} is the pure ice resistance in metric tons.

Bronnikov found that the different powers in the expression are:

$$s = 0.753 F_n^{0.278}$$

$$m = 0.308 F_n^{-0.61}$$

$$n = 0.79 F_n^{-0.49}$$

$$p = 1.759 F_n^{0.75} + 0.35$$

$$q = 2.5 F_n^{0.455} - 0.6$$

$$r = 38.36 F_n^{2.356} + 1.25$$

$$k = 0.039 F_n^{-1.24}$$

where F_n is the Froude number

Kashteljan et al. (1968) also developed an equation to estimate the resistance of a ship in a very light ice floe field based on the modeling of some Russian icebreakers. Their equation is:

$$R_{ip} = \rho_i \sqrt{rh} \left(\frac{B}{2}\right)^2 \left[K_1 \left(1 + 2\alpha \frac{L}{B}\right) + K_4 f \alpha \frac{L}{B} S_{cm} \right] \\ + K_2 \rho_i rhB (\mu + \alpha_b \tan \alpha_E) + K_3 \rho_i rhL \tan^2 \alpha_E F_n^3 \quad (17)$$

where R_{ip} = ice resistance of a ship in an ice field of small broken pieces in kg, and

r = length or extent of pieces of ice in meters.

German and Lawrence (1975) proposed a linear relationship to estimate ship speed in a partial cover (ice floe field). Their equation assumes that ship speed in a partial cover depends on ship speed in open water, ship speed in breaking the same thickness of continuous ice and ice concentration of more than 5/10. The equation is:

$$V_p = V_o + (V - V_o) \frac{(S - 0.5)}{0.5} \quad (18)$$

where V_p = ship speed in partial cover

V = ship speed in solid uniform continuous cover (with no pressure) of the same thickness as the prevailing thickness of ice floes

V_o = ship speed in open water

s = fraction of ice cover (over 0.5).

The equation used in the transit model for resistance in pack ice is a modified form of the Kashteljan et al. (1968) equation (eqn. 15). The equation was modified to allow for variations in concentration and the resulting form is:

$$R = C_{\text{con}} (3.77)(10B) h^{1.2} (C_k + 9v^{1.3})$$

where C_{con} is a reduction factor for lower concentrations

= 1 for 9/10 concentration

2/3 for 8/10 concentration

1/2 for 7/10 concentration

1/3 for 6/10 concentration

For floe concentrations less than 5/10, ship speed is computed from the formula:

$$V = 0.9 V_{\text{open}} + (1 - \text{Conc})(0.1 V_{\text{open}})$$

where V_{open} is the ship's open water speed.

A.1.3 Ship Ramming Into Ice

Any ship navigating in ice may have to resort to the process of ramming when the thrust available from its propellers is not large enough to overcome the resistance generated from the interaction between the hull and the ice. This happens when the ship encounters ice thicknesses beyond its design capability for operating in a continuous ice sheet, or when ice pressure is excessive. The process of ramming involves the following steps:

1. backing a sufficient distance to gain momentum
2. speeding forward in the ice channel
3. riding on and breaking the ice
4. extraction from the ice and backing again.

There is no direct method for calculating ship resistance during

the ramming process; however, there have been several theoretical investigations as well as field measurements of the forces developed at the bow of an icebreaker while ramming.

Based on the principal of conservation of energy and on the work of both Vinogradov (1946) and White (1965), a simple mathematical model to calculate ship's advance during each ramming cycle was developed. Some assumptions have been employed which help to simplify the calculations. By equating available energy (crushing energy + potential energy + friction energy) the following formula was derived:

$$\begin{aligned} & \left[\frac{1}{2} \sigma_i \tan \alpha \tan \beta \right] h x^2 - T x - (1.2) \frac{\Delta}{2g} v^2 + \frac{1}{2} \left(\frac{1}{\rho_w A_{WLF}} + \frac{g^2}{\Delta G M_L} \right) \\ & [F_v^2 (1 + \frac{\mu \cos \alpha}{\sin \alpha \mu \beta}) + 2 F_v \mu T] = 0 \end{aligned} \quad (19)$$

This equation gives the relation between the vertical force developed on the ice edge F_v , and the ship's horizontal advance x .

The vertical force required to break an ice wedge was calculated by Nevel (1967). From Nevel's solution, Lewis and Edwards (1970) generalized the results to handle different boundary conditions by including the total ice sheet divided into wedges. Their simplified result is:

$$F_v = C \sigma h^2 \quad (20)$$

The value of C varies between 0.54 and 0.67 according to different investigations. Substituting equation (20) into equation (19) we get

40% increase due to added mass of water

$$\begin{aligned} & \left[\frac{1}{2} \sigma_i \tan \alpha \tan \beta \right] h x^2 - T x - (1.2) \frac{\Delta}{2g} v^2 + \frac{1}{2} \left(\frac{1}{\rho_w A_{WLF}} + \frac{q^2}{\Delta G M_L} \right) \\ & \left[(Coh^2)^2 \left(1 + \frac{\mu \cos \alpha}{\sin \alpha \cos \beta} \right) + \frac{2(Coh^2) \mu T}{\cos \beta} \right] = 0 \end{aligned} \quad (21)$$

This equation gives the relation between ice thickness (h), approaching speed (v), and advance (x) for a particular ship. If we know the properties of the ice ridge (σ_i , σ , width) and ship particulars (α , β , ...), then from equation (21) we can calculate the number of ramming cycles required to cross the ridge.

The total time required to break an ice ridge depends on both the number of ramming cycles, and the time required for each cycle, or:

$$T_R = N \times T_C \quad (22)$$

where T_R = total time required to break through a ridge

T_C = ramming cycle time

The time required for each ramming cycle depends mainly on ship characteristics and power and can be divided into:

1. time spent in ramming;
2. time spent in backing;
3. time spent in accelerating prior to impact;
4. time spent in freeing the ship and manoeuvring.

A.2 Transit Model Description and Application

The transit model considers seven modes of ship operation:

- i) in open water, denoted O
- ii) in pack ice of concentration less than 6/10, denoted L
- iii) in pack ice of concentrations equal to or greater than 6/10, denoted F
- iv) in continuous ice, denoted C
- v) in non-uniform ice such as ridges, denoted R
- vi) in multi-year ice or iceberg infested water, denoted A or B
- vii) in multi-year ice embedded in pack ice, denoted S

The information required for each mode is:

- O - distance of open water
- L - distance and concentration of floes
- C - distance
average thickness of ice
coefficient of friction
flexural strength
- F - distance
concentration
diameter of floes
thickness of floes
- R - width of ridges
height of ridges
crushing and flexural strength
- A,B,S - distance

Each of these parameters is discussed below.

Flexural Strength

Measured and calculated values of the flexural strength of ice suggest that the flexural strength varies between 0.2 MPa in the case of high salinity and high temperature and 1.2 MPa in the case of low salinity and low temperature. Pack ice strengths are thus expected to be somewhat lower than those of Lake Melville ice. Flexural ice strengths as calculated from compressive strength measurements made on Lake Melville during the present program resulted in an average strength of 1.3 MPa.

Researchers generally agree that the flexural strength is not overly significant since the component of icebreaking is small compared with the other terms in the ice resistance equations. In this study, the following flexural strengths are used for non-ridged ice:

December to April	1 MPa
May to July	0.5 MPa

It is difficult to find a reasonable value for the flexural strength of a ridge as the properties of ridges depend on many factors, such as the original ice sheet thickness and properties, pressure on the ice sheet due to wind and current, and also the age of the ridge (new or old ridge). Usually ridges are formed of broken ice pieces and water pockets and generally the porosity of ridges is between 20% and 50%. An average value for ridge flexural strength has been taken to be 0.25 MPa. It should be noted that most of the energy supplied by the ship (kinetic energy, and propeller energy) is dissipated in crushing the ice

rather than bending it and, as a result, the flexural strength of a ridge does not have much effect on the penetration of the ship into the ridge during ramming.

Crushing Strength (ridges)

Little information is available on the crushing strength of ridges and for the purposes of this study, it has been assumed that the strength will be 1.2 MPa for the period December to April and one-half this value for the remaining months. This value is not unrealistic since the crushing strength of a homogeneous ice sheet is considered to vary from 1.5 to 2.45 MPa (Michel, 1978) and due to the non-consolidation in a ridge, the strength of the latter should be considerably lower.

Ice Strain Modulus

The modulus of elasticity (E) of ice also depends on the ice temperature and salinity. E is defined, in the case of ice, using the tangent to the force deflection curve through the point of origin. Usually E is calculated from simple beam formulae, or from a non-destructive ice sheet deflection test. As an average value the modulus of elasticity of ice as related to flexural strength is often used. In this study, a value of $E = 500$ MPa is used.

Ice Thickness

Although the ice in the study area does not occur as a smooth uniform sheet, existing equations for calculating ship resistance in continuous ice are based on the assumption that the ship breaks a uniform

ice sheet. The uniformity of an ice sheet is very much distorted by environmental factors such as wind, wave, current and temperature fluctuations.

The model uses ice thickness data available from ice charts, measured thicknesses and theoretical values calculated from ice growth equations and considers variations in ice thickness with location and times of season. In the case of Lake Melville, the thermodynamic thicknesses have been calculated from the freezing degree-day record of the Goose Bay weather station and a further 30% has been added to the thicknesses to allow for the particular freeze-up processes that can occur on the lake. The following ice thicknesses are used for Lake Melville and the offshore pack:

- First Year Ice (according to AES information)

	<u>Lake Melville</u>		<u>Pack</u>	
	<u>1st half of month (m)</u>	<u>2nd half of month (m)</u>	<u>1st half of month (m)</u>	<u>2nd half of month (m)</u>
D	0.40	0.50	0.50	0.60
J	0.65	0.80	0.70	0.80
F	0.90	1.00	0.90	1.00
M	1.07	1.07	1.10	1.20
A	1.12	1.12	1.20	1.10
M	1.00	0.80	1.00	0.90
J	0.65	0.30	0.80	0.70
J	0.20	0.10	0.60	0.50

- Grey white ice	0.225 m
- Grey	0.125 m
- Nilas	0.100 m
- Ridges	6 m
- Hummocks	4 m
- Rafted ice	2 times first-year thickness

Coefficient of Friction

The coefficient of friction between ice and a ship's hull is an important factor in calculating total ship resistance in continuous ice. Changes in the value of the coefficient of friction affect the value of the resistance as demonstrated by the resistance equation of Enkvist. The coefficient of friction between the ship's hull and ice depends on several factors including:

1. ship hull surface finish
2. snow on ice
3. puddling on ice
4. ice temperature

The following coefficients have been used in this study with an increase reflecting possible increases in snow cover during late winter months:

D	0.25
J	0.25
F	0.35
M	0.35

A	0.35
M	0.25
J	0.25
J	0.25

The coefficient of friction when operating in floe ice is assumed to remain constant at 0.1 and when in ridges, hummocks and rafted ice is assumed constant at 0.30.

Floe Size

In the AES Ice Charts floe diameters greater than 100 m are reported; otherwise it is assumed that floe sizes are less than this. From other data available as discussed in Section 3.4.2 of the main report, an average general diameter has been taken as 30 m. Large floes as reported by the Ice Charts are considered to have an average diameter of 300 m.

Ice Data

Data of ice conditions for use in the computer model were obtained from AES Ice Central Charts for the eleven years 1969-1979. Ice conditions portrayed on the ice charts are determined from overflights, satellite imagery, and weather forecasts. The charts were projected upon a 'digitizer' table (Talos series 600 Cybergraph system) and the distances over which the different ice conditions prevailed along a 541 km track from Northwest Point in Lake Melville to 52°W longitude were measured and coded.

A computer file was created from the AES ice chart data containing, for each 541 km track, the distances in kilometers between the boundaries of different ice conditions and for each such distance, coded ice information describing the prevailing ice conditions. A typical 541 km track is described as follows:

Day,Month,Year,Number of Segments in the track
Distance of Segment 1, code for segment 1
Distance of Segment 2, code for segment 2
etc.

Since the AES code for a single distance segment contains information regarding several ice types, each segment was subdivided into smaller "homogeneous" segments based on ice type, etc. so that specific information could be provided as input to the transit model computer program. This subdivision was accomplished as follows:

- i) if the total distance D was open water or bergy water, the code '0' or 'B' and the distance D are output
- ii) the total concentration C is determined, and if $C < 6/10$, the code 'L', distance D and concentration C are output;

If $C \geq 6/10$, the number (NTYP) of different types of ice present is computed. The possible types are:

Multi-year

First year, Grey-white, Grey, Nilas (small floes)

First year, Grey-white, Grey, Nilas (large floes)

If the concentration C is less than 10/10 this number will be used to distribute the amount D_0 of open water ($D_0 = D(1-C)$)

throughout the various types of ice. For each type, in concentration C_T , the distance over which the type prevails is computed as:

$$D_T = C_T * D + C_T D_0 + \frac{(1-C)^2 D}{NTYP}$$

This formula distributes through a particular type an amount of open water proportional to the concentration of that type.

$$\begin{aligned} \text{(Since } \sum_1^{NTYP} C_T &= C, \sum_1^{NTYP} \frac{(1-C)^2 D}{NTYP} = (1-C)^2 D, \text{ and } D_0 = (1-C)D \\ \text{then } \sum_1^{NTYP} D_T &= CD + C(1-C)D + (1-C)^2 D \\ &= CD + CD - C^2 D + D - 2CD + C^2 D \\ &= D \end{aligned}$$

and so the total distance is distributed).

- iii) First year, grey-white, grey and nilas concentrations are divided into distances of small floes and large floes based on the AES code. The output information in each case is:

code 'F', distance, thickness, floe size, concentration, coefficient of friction

- iv) If concentrations of ridging, hummocking or rafting occur in the AES code they are assumed to apply to first year large floes. The distances over which these phenomena occur are computed as:

$$D_I = (DFYL = \text{distance of first year large floes}) \times (\text{concentration of phenomena})$$

Ridges are assumed to be 25 m wide and to occur with a frequency of 2 per km. Since the model cannot distinguish between a

number of such ridges and a single ridge of the total width, a distance representing the total width of ridges is computed.

$$D_{RI} = D_I \times 2 \times 0.025$$

DFYL is then reduced by D_{RI}

The output code for ridging is:

code 'R', distance, thickness, coefficient of friction

The distance over which hummocking occurs is:

$$D_{Hu} = D_I$$

and DFYL is reduced by D_{Hu}

The output code for hummocking is:

code 'F', distance, thickness, size of floes, coefficient of friction, concentration.

Rafting is assumed to occur over 250 m per km so the distance of rafted ice is:

$$D_{RA} = D_I \times 0.25$$

DFYL is reduced by D_{RA}

The thickness of rafted ice is assumed to be twice the thickness of the first year ice.

The output code for rafting is:

code 'F', distance, thickness, concentration, size of floes, coefficient of friction

- v) If the concentration C is 10/10 then in (iii) and (iv) above (except ridged ice) the code letter 'F' is changed to 'C' and

the coefficient of friction is changed to that of continuous ice.

- vi) The distance over which multi-year ice occurs is computed. If first year ice prevails over the same segment the output code is:

code 'S', distance

If no first year ice prevails, the output code is:

code 'A', distance

Ship Parameters

The ship parameters used in the various resistance equations are listed in Table A.1 for the three ships considered in the model.

Ship Speed

The model uses the ice and ship parameters to compute transit times by calculating the speed at which the ship may proceed over a given distance under a particular condition. The speeds for the different modes of operation are determined as follows:

- O - In open water, the speed used is the normal cruising speed (V_{open}) of the ship.
- L - In a floe field of less than 6/10 concentration the speed V is given by the formula:

$$V = 0.9 V_{open} + (1.-\text{concentration})(0.1 V_{open})$$

- C - The speed in continuous ice is obtained by solving the equation $R_c(V) - T(V) = 0$ for speed V , where $R_c(V)$ is the resistance equation for continuous ice, and $T(V)$ is the thrust equation

TABLE A.1

Ship Parameters Used in the Various Resistance Equations
for the Three Ships Considered in the Model

	M.V. ARCTIC	C.C.G.S. FRANKLIN	C.C.G.S. LOUIS ST. LAURENT
HP - shaft horsepower (metric)	14770	13605	24000
T_o - Bollard pull* (metric tons)	160	122	230
Δ - displacement (metric tons)	38104	6600	14509
V_{open} - normal open water speed (m/s)	7.72	6.94	6.69
V_{max} - maximum open water speed (m/s)	8.75	8.31	9.10
L - length (metres)	196.696	98.	111.7
B - breadth (metres)	22.86	19.5	24.4
D - draft (metres)	10.928	6.2	9.5
SF - submersion depth (metres)	7.65	4.65	6.175
HBW - height of bow wave (metres)	0.2	0.2	0.2
AWLF - area of water plane of entrance (m^2)	393.9	153.2	200.0
LMH - longitudinal metacentric height (m)	200	100	110
ϕ - angle between stem and horizontal plane	30	28	30
ψ - angle between a horizontal plane and section perpendicular to waterline	53	46	46
α - half-angle of entrance of a waterline	33	30	35
β - angle between section and vertical plane	46	42	42
V_R - ship forward speed during ramming cycle (m/s)	5.0	5.0	5.5
CTM - ramming cycle time (min.)	6.0	5.0	5.0

*If the Bollard pull value for a ship is unavailable, it is computed by the relation:

$$T_o = 0.008826 \cdot HP$$

If the open water speed for a ship is unavailable, it is computed by the relation:

$$V_{open} = 0.994 \cdot \sqrt[3]{\frac{0.7355 \cdot HP}{\Delta}}$$

$$T(V) = \frac{-2T_0}{3V_{open}^2} \cdot V^2 - \frac{T_0}{3V_{open}} \cdot V + T_0$$

If there is no positive solution to $R(V)-T(V) = 0$, the transit time is computed as in "R" below.

- F - The speed in a floe field of greater than 5/10 concentration is obtained by solving the equation $R_F(V)-T(V) = 0$ for speed V , where $R_F(V)$ is the resistance equation for floes and $T(V)$ is the thrust equation. If the solution V is greater than 95% of V_{open} the latter is used. If no positive solution exists the model proceeds as in "C" above.
- R - In a ramming mode no speed is computed - the transit time is computed as follows: the ship advance x in each ram is obtained from the resistance equation $R(x) = 0$, and this distance is divided into the total distance to give the number of rams required, which is multiplied by the ramming cycle time.
- A,B - the speed in water containing multi-year ice fragments or icebergs is assumed to be 70% of open water speed.
- S - the speed in pack ice containing multi-year ice fragments is assumed to be equal to the speed in first year pack ice.

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LAKE MELVILLE/OFFSHORE LABRADOR YEAR-ROUND

NAVIGATION STUDY, 1978-79

APPENDIX B

PRELIMINARY CONSIDERATIONS FOR CARGO SHIP DESIGN

Submitted to: NORDCO Limited

Submitted by: German and Milne Inc.,
Montreal

PRELIMINARY CONSIDERATIONS FOR CARGO SHIP DESIGN

EXECUTIVE SUMMARY

A study of the worst ice conditions to be encountered, when navigating from the Labrador Sea down to Northwest River passing through the Narrows and Lake Melville, indicates the following:

A. Year Round Navigation Un-Assisted by Icebreakers

Year round service should be possible by cargo vessels having the construction and power to progress continuously through 4 feet thick solid ice and progress by ramming through 20 feet thick rafted ice. Three sizes of such vessels have been considered here as suitable.

DWT	L.B.P. M	BREADTH M	DEPTH M	B.H.P. (twin screw)
10,000	131.5	19.1	11.6	19,600
20,000	163.1	22.6	13.8	22,500
30,000	185.7	25.0	15.4	24,400

B. Year Round Navigation Assisted by Icebreakers

If icebreaker assistance is available from about mid December to about mid May then year round service should be possible by cargo vessels having the construction and power to progress through 2 feet thick solid ice. Principal particulars for such vessels would be almost identical to open water ocean going vessels.

DWT	L.B.P. M	BREADTH M	DEPTH M	B.H.P. (single screw)
10,000	125.6	18.4	11.2	6,500
20,000	158.2	22.0	13.5	9,000
30,000	181.1	24.5	15.1	10,500

C. Seasonal Navigation Without Icebreaker Assistance

Vessels having the construction and power similar to those in the preceding Paragraph B should be able to navigate independently from about mid May to about mid December.

GENERAL :

The object of this study is to recommend optimum specifications for cargo ships (of 10,000 DWT, 20,000 DWT, 30,000 DWT), which shall be capable of negotiating pack ice and traversing Lake Melville down to Northwest River on a year-round basis.

The extent of funding for this report is such that input is not with the greatest detail and, therefore the offered data, results, and conclusions are to be considered as approximate and at best should be used for guidance and general policy making.

Should prospects advance to firm commitments in material progress, then a much more detailed study should be funded.

Ships negotiating this route will have to navigate through three principal areas, i.e. 1) The Labrador Coast, 2) the Narrows, and 3) Lake Melville.

The principal dimensions, hullform, bowshape, and icebreaking performance of the above ships will depend on the thickness and coverage of ice that will be encountered on the route.

The study, therefore, has been divided into three parts.

- 1 - Ice Description
- 2 - Route Description
- 3 - Ship Design

PRELIMINARY CONSIDERATIONS FOR CARGO SHIP DESIGN

PART I

ICE DESCRIPTION

Ice data, to the extent of applicability for this study, has been extracted from two sources:

- 1) "Marine Environmental Data" by Marsaw Investment Ltd.
- ii) "Labrador and Hudson Bay Pilot" issued by Canadian Hydrographic Service

AREA I

LABRADOR COAST / HAMILTON INLET / GROSWATER BAY

The ice in this area is a mixture of locally formed ice and ice that is carried southward in the Labrador Current. Thin "imported ice" grows thicker as the season progresses both because of the accumulated Freezing Degree Day total and, because the source area is further and further up the Labrador or Baffin Island coast.

In April, May and June, the ice in the area may have originated from Northern Baffin Bay (in some seasons) and as a result, some old ice may be present if appropriate intrusions into Baffin Bay occurred the previous autumn. There appears to be a tendency (due to a lack of acceptable data) to over-report the amount of this old ice for it is difficult to imagine how such intrusions could ever amount to more than a few percent of the total ice cover in this area even after some of the first year ice has melted. There are some reports in this area up to 20% old ice but these are likely exaggerated and 2 - 5 % is probably more accurate.

- 35 -

Average Date Ice Formation begins 1 December
Average Date Ice Reaches Max. Thickness 15 April
Average Date Puddling begins 10-15 May
Average Date Thaw Holes appear 5-10 June (Does not always occur)
Average Date 6/10 Ice Covers occurs 14 May
Average Date 3/10 Cover occurs 11 June
Average Date Open Water 9 July

Max. Ice Thickness of New Ice Skim to 4"
Max. Ice Thickness of Young Ice 4"-12"
Max. Ice Thickness of One Year Ice 45"-48"
Max. Ice Thickness Rafted One Yr. Ice 15'-20'
Max. Ice Thickness Two Year Ice 10' rarely occurs
Max. Ice Thickness Multi-Year Ice 10' rarely occurs

The Arctic ice pack generally arrives off Hamilton Inlet between the 1st and 15th of February, depending on the wind; if strong northerly winds prevail, it may arrive earlier. Between the 1st and 15th of June the ice loosens up, and westerly winds may drive it offshore, leaving a passage inside among the islands, the pack extending many miles seaward. Under these conditions a passage may be made up the coast in comparative safety, but care must be taken to observe the wind, as the pack ice may be driven against the land again by easterly winds. The coast is not usually clear of drift ice until well into August.

AREA 2

"THE NARROWS" (RIGOLET) CONNECTING GROSWATER BAY WITH LAKE MELVILLE

The Narrows at Rigolet and extending to Eskimo Island do not freeze over as a rule owing to the swift tidal current. This area, however, was frozen for a month during the winter of 1920, and also about 12 years before.

Part 1 (Cont'd)

Ice does not constitute a danger to navigation from Ticoralak Head through The Narrows during the season of navigation.

AREA 3

"LAKE MELVILLE"

Lake Melville is generally frozen over by Christmas, the ice forming along the shores about the first week in November and gradually extending out. The average winter temperature is about -34°C (-30°F). The thickness of ice is about 4 feet (1^m2) but rafted ice may form a thickness of from 10 to 15 feet (3^m0 to 4^m6).

At the western end of the lake, the following areas generally remain open all winter due to swift tidal current; the entrances to Northwest River, Carter Basin, Goose Bay and Hamilton River.

In the spring of the year, the ice in Lake Melville breaks up in April and is mostly gone by the middle of May.

Average Date Ice Formation Begins 19 November
Average Date Ice Reaches Max. Thickness 1 April
Average Date 6/10 Ice Cover Occurs 7 May
Average Date 3/10 Ice Cover Occurs 24 May
Average Date Open Water 4 June
Max. Ice Thickness of New Ice to 4"
Max. Ice Thickness of Young Ice 4" to 12"
Max. Ice Thickness of one year Ice 40" to 45"
Max. Ice Thickness Rafted One yr. Ice 10' to 12'

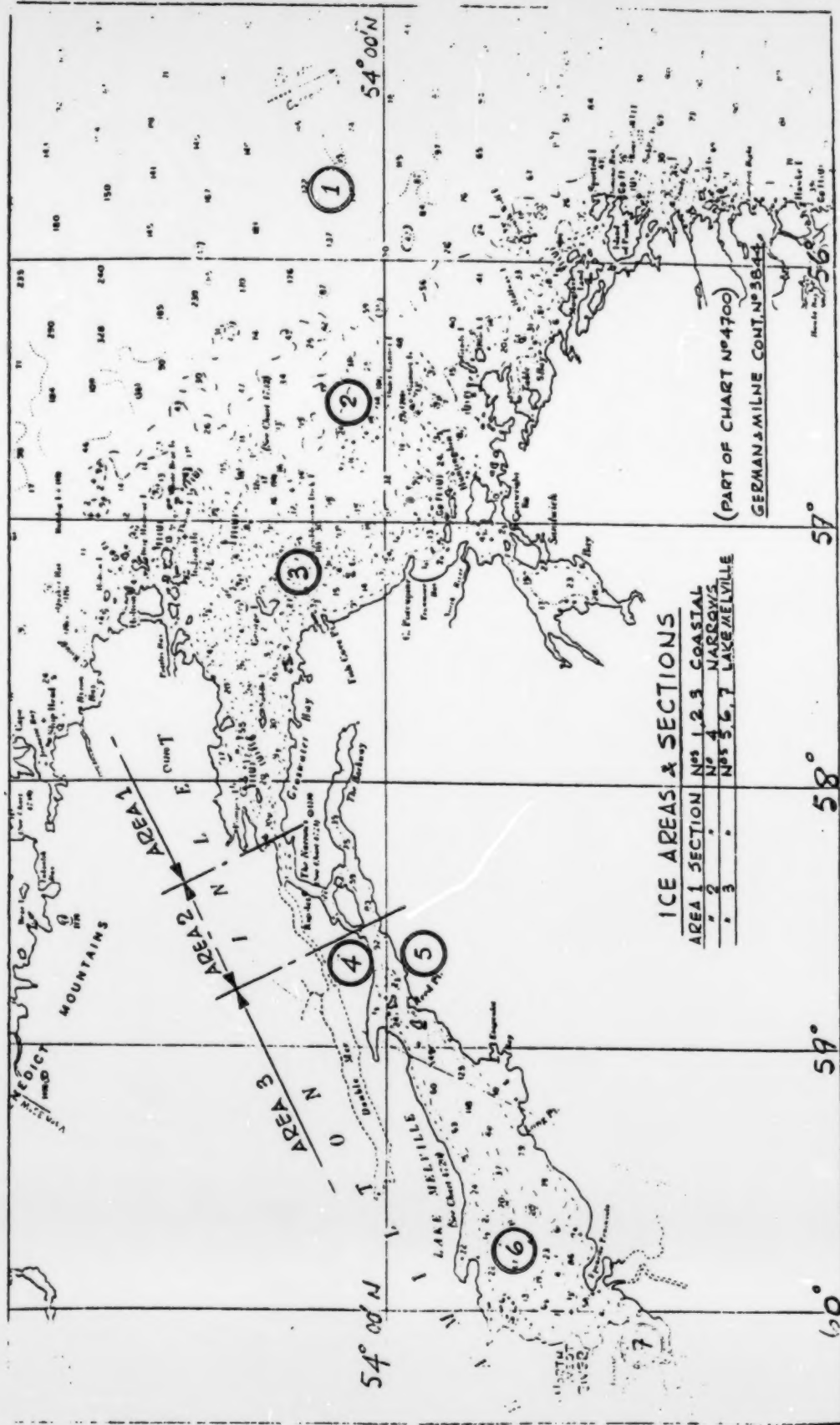
The three broad areas of navigation are further subdivided into 7 sections, and, these sections have been numbered 1 to 7 inclusive as shown on the chart.

SECTION	LONGITUDES	LATITUDES
1	55°W to 56°W	North of 54°N
2	56°W to 57°W	" " "
3	57°W to 58°W	" " "
4	58°W to 59°W	" " "
5	58°W to 59°W	South of 54°N
6	59°W to 60°W	" " "
7	60°W to 61°W	" " "

The ice coverage over these sections for particular time periods of the year are shown in the following table. Ice coverage is considered in tenths where 10/10 is solid ice and open water is 1/10 or less. Any intermediate figure represents areas with proportionate openings in the ice.

STUDY AREA	SECTION	ICE COVER IN TENTHS		PERIOD
		MAXIMUM	HIGHEST AVERAGE	
1. COASTAL & OFFSHORE	1	9/10	9/10	5th Feb. to 19th Mar.
	2	9/10	9/10	12th Feb. to 9th Apr.
	3	9/10	9/10	1st Jan. to 2nd Apr.
2. NARROWS	4	10/10	10/10	" " "
3. LAKE MELVILLE	5	10/10	10/10	" " 23rd Apr.
	6	10/10	10/10	" " "
	7	10/10	10/10	11th Dec. to 21st May







ROUTE DESCRIPTIONHAMILTON INLET

Directions: The precautions usual in unsurveyed waters should be taken when navigating the outer part of Hamilton Inlet.

Vessels approaching from seaward have their choice of two recommended tracks, which join in a position to the north-northeastward of George Island.

The southern of these two tracks leads in westward along the parallel of Lat. $54^{\circ} 11' 05''$ N., passing about 4 miles southward of the southernmost of the Southeast Rocks, to a position about 5 miles east-northeastward of Tumbledown Dick Island. It then leads northwestward along a course of 315° for a distance of $12\frac{1}{2}$ miles to its junction with the northern track, in a position about 3 miles north-northeastward of the northeastern extremity of George Island.

It has been reported that the northern and eastern approaches to Hamilton Inlet are invariably closed by ice in the early part of the season. It is recommended that vessels encountering such conditions should use the southern approach which, though not entirely free of ice, has the advantage of generally lacking pressure ice.

The northern track leads in westward along the parallel of Lat. $54^{\circ} 21' 38''$ N., passing about $4\frac{1}{2}$ miles northward of the northernmost of the Southeast Rocks and about $5\frac{1}{2}$ miles southward of East Rock, to a position about $1\frac{1}{2}$ miles northward of Herring Islands light. It then leads west-southwestward along a course of 256° to its junction with the southern track. From this junction vessels steer westward to Groswater Bay.

Part 2 (Cont'd)

HAMILTON INLET (Cont'd)

Depths: The area along the northern track has been wire dragged to a depth of 6 fathoms + 5 feet. The outer part of Hamilton Inlet has general depths of 20 to 40 fathoms (36^m6 to 73^m2)

GROSWATER BAY

Directions: From the junction of the two seaward approaches in Hamilton Inlet, vessels should steer westward to pass about 2½ miles northward of George Island and about half a mile southward of Black Island, taking care to keep northward of the 37 foot (11^m3) patch situated about 3½ miles southward of the southern Twin Island. From a position southward of Black Island, vessels should steer in a general west-southwesterly direction to pass mid-way between Big Island, on the north, and East Sister Island, on the south, and then mid-way between Ticoralak Head and the coast southeastward. When Ticoralak Head is abeam, vessels should steer for Double Mer Point, favouring the northern shore, until Strathcona Point comes to bear less than 220° and is well open of the eastern shore of the Narrows, at which time they will be well past Man of War Rock and may alter course south-southwestward for Rigolet.

GROSWATER BAY

Directions: (Cont'd)

Groswater Bay, which forms the outer part of Hamilton Inlet, is entered between Pottles Cove Head (Lat. $54^{\circ} 10'$ N., Long. $57^{\circ} 21'$ W.) and Man of War Point, 22 miles north-northwestward. The bay, which contains several large islands, trends westward for about 38 miles.

The northeastern approaches are much encumbered by the White Bear Islands and the numerous islands and islets westward of them. The southeastern part of the entrance is similarly encumbered but to a much lesser extent. The main entrance to the bay lies between the northern extremity of George Island (Lat. $54^{\circ} 17'$ N., Long. $57^{\circ} 18'$ W.) and Double Island, 8 miles northward.

Depths: General depths of between 12 fathoms (21^m9) and 40 fathoms (73^m2) exist in Groswater Bay although isolated banks with depths of between 6 and 9 fathoms (11^m0 and 16^m5) occur in its central part.

The main channel through the bay, which passes northward of Little Black Island and southward of Big Island, has been wireswept to a depth of 42 feet (12^m8) and no obstructions found.

Shipping Control: The Harbourmaster at Goose Bay is in control of shipping from Groswater Bay to the docks at Terrington Basin.

THE NARROWS

Directions: The Narrows is the passage connecting Groswater Bay with Lake Melville and is entered from the northeastward between Lester Point (Lat. $54^{\circ} 12'$ N., Long. $58^{\circ} 21'$ W.) and Double Mer Point.

THE NARROWS (Cont'd)Directions: (Cont'd)

It extends south-westward, with an average width of a little over a mile, for about 6 miles, where it is divided into two channels by Henrietta Island, which lies in the southern entrance. Cul de Sac, the channel westward of Henrietta Island, is the one normally used. This western channel is further divided by Eskimo Island, a small island lying in the middle of the entrance to Lake Melville. The passage eastward of Eskimo Island is the one generally used.

From Rigolet a mid-channel course is steered through The Narrows, vessels passing down the western side of Henrietta Island and between Henrietta and Eskimo Island.

Depth: Mid-channel depth in The Narrows are somewhat uneven but ample for deep-draught vessels. The least known depths are $7\frac{1}{2}$ and 8 fathoms (13^m4 and 14^m6) in mid-channel abreast of Rigolet.

Tidal Currents attain a rate of 5 knots at spring ebb tides, and 4 knots at flood. During neap tides the flood and ebb are about 3 knots.

Ice does not constitute a danger to navigation from Ticoralak Head through The Narrows during the season of navigation.

Pilots: Pilots are available at Rigolet for vessels proceeding to Terrington Basin.

Anchorage: Vessels awaiting a pilot or suitable conditions of tide or daylight for passage through The Narrows usually anchor off the entrance to Collinghams Cove. Anchorage is also obtainable in Rigolet Cove in 7 fathoms (12^m8), mud, with the easternmost wharf bearing 240° - 3 cables.

THE NARROWS (Cont'd)

This berth is out of the tidal current but the holding ground is not good. Large vessels anchor farther offshore in the current. Such a vessel, drawing 29 feet (8^m8), anchored off Rigolet for four hours in a strong ebb current, found the holding ground adequate.

LAKE MELVILLE

Directions: After having cleared The Narrows vessels then pass southward of Gull Island taking care to avoid Lareto Shoal.

Vessels should favour the southern shore in this area as other dangers and suspected dangers are believed to exist in this area. They then pass between Neveisik and St. John Island, thence between Green Island and Charley Point, and then direct to a position midway between Blake Shoal and Epinette Point. Great care must be taken in the approach to Epinette Point as the presence of a northerly set during ebb tide makes Montagnais and Blake Shoals and Cartier Shoal, 3½ miles northeastward of Blake Shoal, potentially dangerous.

Tides: Tidal predictions for Lake Melville are contained in the "Atlantic Coast Tide and Current Tables".

NORTHWEST RIVER

Directions: Approach to North West River. From Montagnais Point the coast trends south-southwestward for 3½ miles to the entrance to North West River. This section of the coast is shoal for about three-quarters of a mile offshore at the eastern, and about half a mile at the western end. From the southern side of the river mouth, the sandy shore trends southeastward for 2 miles to Bottle Point, then irregularly east-northeastward for 1½ miles to North West Point, thus forming The Bight, about 3½ miles wide, between Montagnais Point and North West Point. There are no dangers outside the 6 fathom (11^m0) contour.

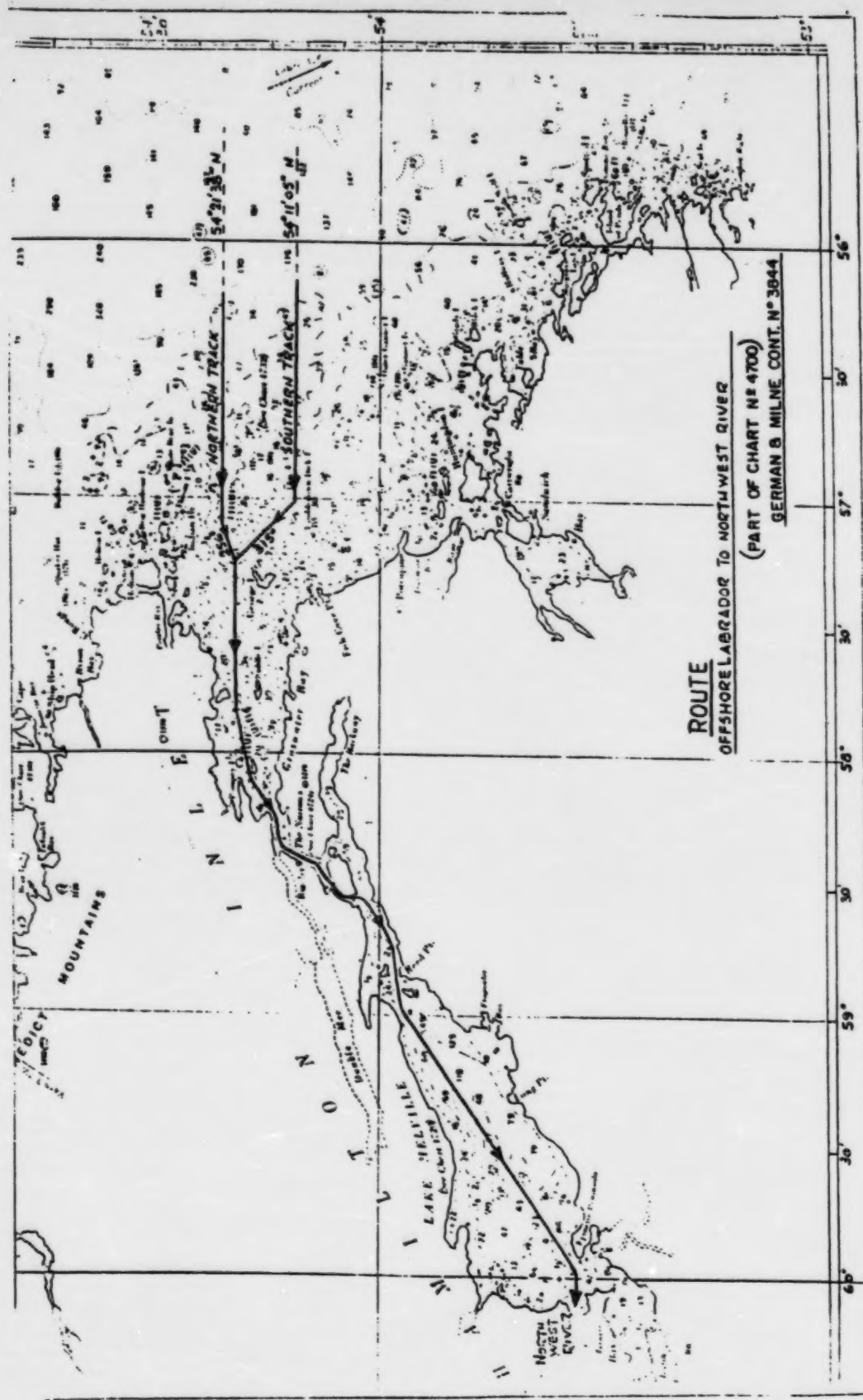
NORTHWEST RIVER (Cont'd)

Directions: (Cont'd)

The settlement of North West River (Lat. $53^{\circ} 31' N.$, Long. $60^{\circ} 09' W.$) is situated on the northern shore of the river.

Depths: There is a wharf on the north side with a depth of 8 feet (2^m4) at its outer end. It is suitable for small craft, and supplies are unloaded at the anchorage and brought to the wharf in barges.

Tidal Currents: At the entrance, in The Narrows, to Grand Lake, the normal current was found to be $3\frac{1}{2}$ knots, and at the entrance to North West River it ranged from $2\frac{1}{2}$ knots at neap tides to $4\frac{1}{2}$ knots at spring tides.



ROUTE

OFFSHORE LABRADOR TO NORTHWEST RIVER

(PART OF CHART NO. 4700)

GERMAN & MILNE CONT. NO. 3844



PART 3

SHIP DESIGN

A GENERAL

In order to select a suitable size of cargo ship to negotiate the route (described in Part 2) a broad range of sizes has been considered first. To cover the range of sizes, three particular ships sizes have been chosen: 10,000 DWT; 20,000 DWT; 30,000 DWT.

Published data of ocean-going cargo ships built for open water navigation only, indicate the following:-

DWT	DISPL. TONNE	L.O.A. M.	L.B.P. M.	BEAM M.	DEPTH M.	DRAFT M.	SPEED KNOTS	B.H.P. SINGLE SCREW
10,000	13,680	133.6	125.4	18.4	11.2	8.3	15.5	6,500
20,000	25,700	168.3	158.0	22.0	13.5	9.6	15.5	9,000
30,000	38,460	192.7	180.9	24.5	15.1	10.6	15.5	10,500

However, for winter navigation over the subject route, special considerations have to be made as follows:

- a) Hull Structure, Propulsion and Stern Gear to be suitable for:
 - i) Continuous progress through solid ice cover of 4ft. thickness, ie. similar to an Arctic class 4 ship.
 - ii) Progress by ramming through rafted ice of up to 20ft. thickness in costal areas and up to 12 ft. thickness in Lake Melville.
- b) The average winter temperature is about 30°F below zero and therefore suitable installations will be necessary for:
 - i) Habitability
 - ii) Equipment
 - iii) Outfit

Part 3 (Cont'd)

c) The draft will have to be limited to a maximum of 6 fathoms (10.97m) due to:

- i) The recommended track in Hamilton Inlet and Groswater Bay having been wire dragged to only a depth of 6 fathoms and 5 feet (i.e. 12.50m)
- ii) The minimum depth at The Narrows being only 7 fathoms and 2 feet (i.e. 13.41m)
- iii) The minimum safe depth near Northwest River being only 6 fathoms (i.e. 10.97m).

d) The maximum beam will have to be limited to minimize the propulsion power requirement. For icebreaking vessels, in general, the lesser the beam the lesser will be the required power. However, the minimum beam shall be to suit stability requirements in open water.

e) Limitations on beam and draft will necessarily require adjustment to length and depth in order to maintain the required cargo volume.

f) Machinery size, fuel capacity, ballast capacity, etc., will further dictate overall dimensions.

B PRINCIPAL PARTICULARS

Based on the preceding considerations the following particulars have been derived for three sizes of cargo ships with structure, machinery, equipment and outfit equivalent to the requirements for Arctic Class 4 vessels. However, since the area of operation is not covered by the CASPP Regulations, the vessel does not need to be built to those requirements.

B PRINCIPAL PARTICULARS (Cont'd)

DWT.	Displ. S.W. Tonnes	L.O.A. M	L.B.P. M	Beam M	Depth M	Draft Full Load M	Speed - Knots		BHP Twin Screw
							Open Water	4' Ice	
10,00C	15,310	140.0	131.5	19.1	11.6	8.5	15.5	3.0	19,600
20,00C	28,080	173.7	163.1	22.6	13.8	9.8	15.5	3.0	22,500
30,00C	41,200	197.8	185.7	25.0	15.4	10.8	15.5	3.0	24,400

C HULL FORM

The hull form for these cargo ships are based on the following:-

- i) Block coefficients in the range 0.70 - 0.80
- ii) Aft body of sufficient size to contain the propulsion machinery with accommodation superstructure over
- iii) Twin screw propulsion
- iv) Mid-body of sufficient volume to contain the cargo, while maintaining a minimum beam for adequate stability.
- v) Fore body of sufficient length to lead from an efficient icebreaking stem to the parallel mid-body
- vi) Full load draft not exceeding 10.97 metres (i.e. 6 fathoms)

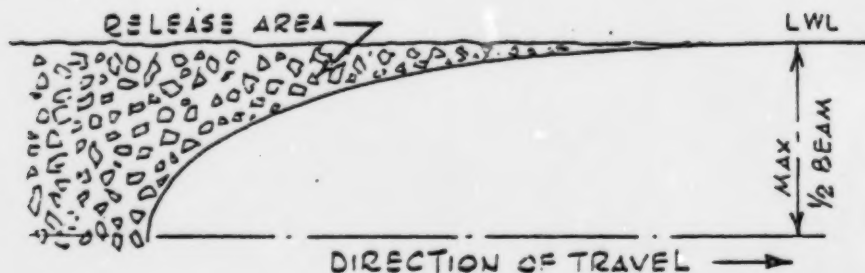
D AFT BODY FORM

The aft body form has a significant impact as to the quantity of ice which comes into contact with the propeller. Notwithstanding the fact that the propeller should be designed to operate under the worst foreseeable operating conditions, ice ingestion can be materially reduced by decreasing the beam of the water line aft of the maximum beam in order to produce a "clear" area

D AFT BODY FORM (Cont'd)

at the side of the vessel providing a "release" space for broken ice to surface and return to a stable condition. (See Fig. 1)

FIG. 1



The underwater form should also be designed with this release of ice approach in mind and, although the designer may be frustrated somewhat when attempting to incorporate wing screws, a good approach is to design the after body with much the same form in mind as that for the forward end. Of course, allowance must be made for such auxiliary spaces such as steering gear, but in general the flare angles can follow the bow section in way of the waterline.

Sufficient overhang should be allowed for protection of the rudder, and in determining the stern contour it must be remembered that eventually any icebreaking vessel will be required to back into an ice field.

A well rounded cruiser stern configuration, or, a transom stern providing sufficient "over ice" clearance, may be adopted. (See Figs. 2 & 3)

D AFT BODY FORM (Cont'd)

FIG. 2

CRUISER STERN

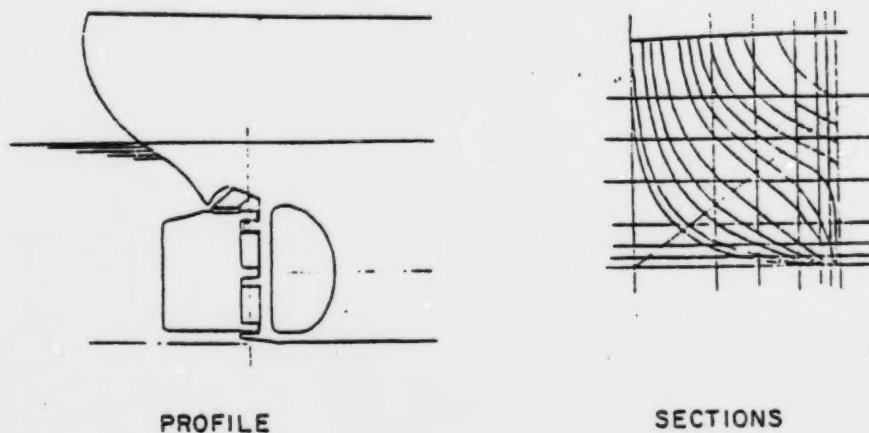
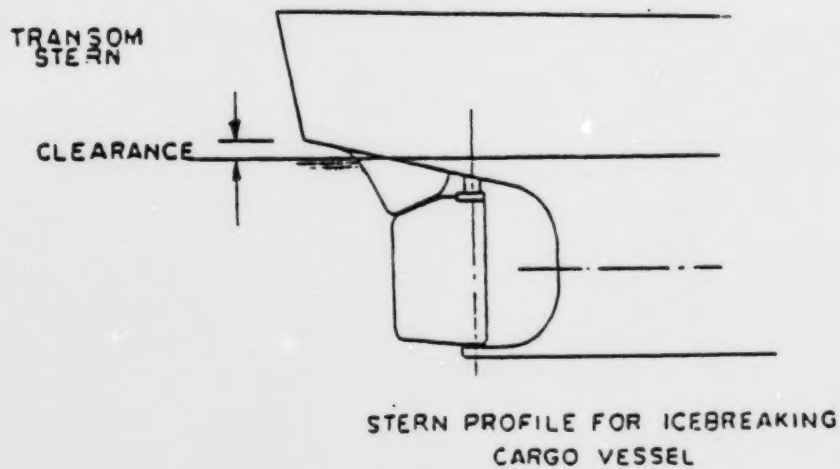


FIG. 3



D AFT BODY FORM (Cont'd)

To offer protection to both the rudder and more particularly the stock, an ice horn (ice knife) is recommended to be fitted, and in fact is required when building to Lloyds and A.S.P.P. Regulations. It is to be remembered that the horn will, in effect, become an ice breaking device when going astern and will either deflect or split an ice pan depending upon the speed of the vessel, the strength of the ice, the size of the pan etc. For this reason the ice horn should be well incorporated into the hull form and structural elements of the vessel.

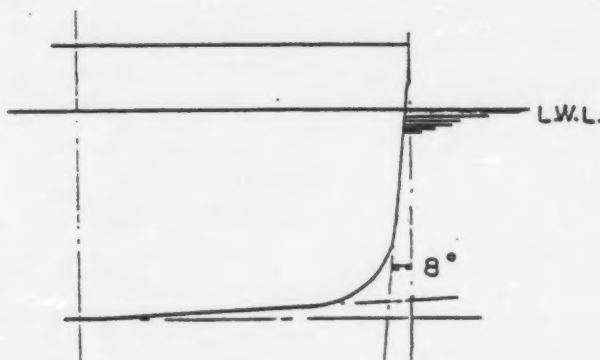
E MID-BODY FORM

Traditionally mid-body flare has been incorporated into professional icebreakers. This practice is a carry over from the days of wooden vessels (ex. Fram) where mid-body flare was considered essential in order to prevent the hull being crushed by ice pressure. It was considered that such pressure would cause the vessel to lift out of the water and thus avoid damage. Vessels with no mid-body flare have operated successfully in Arctic waters, and although there may be some concern regarding crushing, it is felt that with modern all welded heavy steel construction, there is little if any possibility of a vessel being crushed by a compressing field of ice.

While it is true that flare amidships will reduce the direct pressure on the sides of the vessel and no doubt enable the vessel to "break-out" more easily after being beset, it is difficult to envisage a large flare angle solely for this purpose since "break-out" may be achieved in many other less restrictive ways. Disadvantages of large flare at mid-ships includes restricted hull space for cargo or machinery for a given maximum beam, and with the block coefficients in excess of 0.7 associated with the commercial cargo vessels, it is virtually impossible to produce a good set of lines for icebreaking with large mid-ships flare angles. Some advantages may be gained

E MID-BODY FORM (Cont'd)

in the structural elements of the vessel when built to the A.S.P.P. Regulations where the flare angle is 8° or greater, but this saving must be measured against other cost components when evaluating the merits of such a design feature. In practice it would appear that there is some merit in having a measure of flare at mid-ships, and the A.S.P.P. Regulations transition figure of 8° seems to give a practical value for incorporating in design. (See Fig. 4)

FIG. 4F FORE BODY FORM

Results of theoretical analysis and tank testing indicates that the bow angle needs to be between 17° and 25° , that the flare angles over the bow sections should be in the order of 50° - 60° decreasing smoothly to the mid-body flare angle and the waterline half angle of entrance should lie between 30° and 35° .

In general there must be no flat or hollow areas, particularly forward. The form must, in fact, have a good measure of convexity throughout.

From model tests there is no doubt that theoretically, at least, this type of bow shows superior icebreaking features. However, the inherent increased area of contact with the ice sheet, particularly where snow cover is present and subsequent increase in friction will rapidly decrease the effectiveness to the point where the bow form will be more of a hindrance than a help. It is, therefore, recommended that the extremes be avoided and that a more

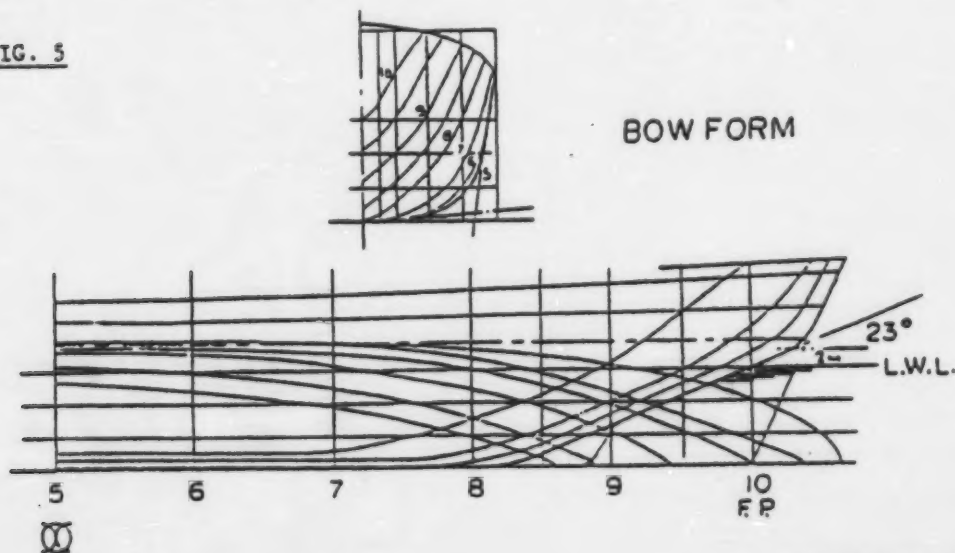
F FORE BODY FORM (Cont'd)

practical bow angle would be in the order of 23° . (See Fig. 5)

Dependent upon the draft of the vessel and the ice conditions expected to be encountered during service, the bow angle may be carried to the keel at a constant angle or curved down to form a "bulb" type forefoot. This latter type of profile would be practical on the more commercial vessels, such as tankers, bulk carriers, etc. where maximum deadweight/length ratios are required. It has been the practice on a large number of vessels to introduce a forefoot, not related to displacement capacity but designed to prevent the vessel from riding up on an ice ridge to a point where

- (a) Extraction is impossible
- (b) Stability is reduced to the point of capsize or
- (c) The longitudinal bending moment becomes critical

Model testing has indicated that some advantage is gained from the forefoot in it's ability to separate the ice driven down the bow and to some degree at least direct the ice pieces sideways rather than passing beneath the vessel and eventually through the propellers.

FIG. 5

GERMAN & MILNE INC.
NAVAL ARCHITECTS

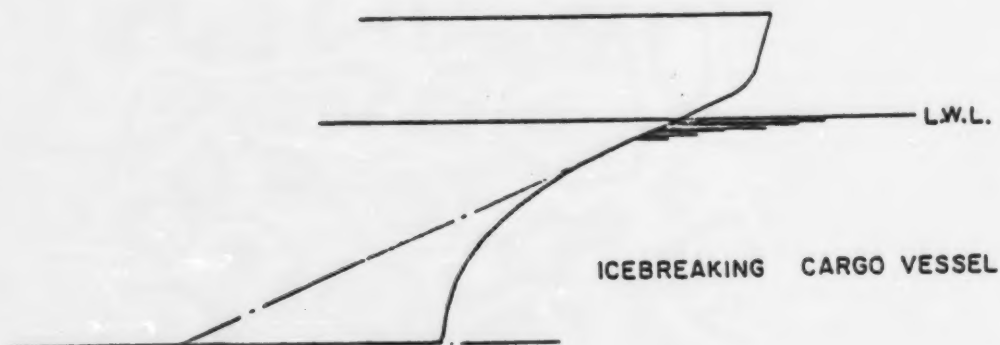
Part 3 (Cont'd)

F FORE BODY FORM (Cont'd)

In addition to the foregoing, the clearance of the bow above the waterline is a further point to be considered in this forebody design and this to a great extent depends upon the amount of rafted or ridged ice the vessel is expected to encounter. Obviously any extensive overhang to obtain good clearance will effect the length of the vessel. Another method to give a measure of protection is to have the turn of the stem above the waterline well rounded to minimize the effect of ice contact.

The flare above the waterline in way of the deck, in past icebreakers, has for the most part been minimal due mainly to the determination to avoid hollow sections. However, there seems to be no grounds for not introducing a moderate flare in this area and in this way alleviate the problem of "wet" foredecks experienced when these vessels are in transit in open waters.

FIG. 6

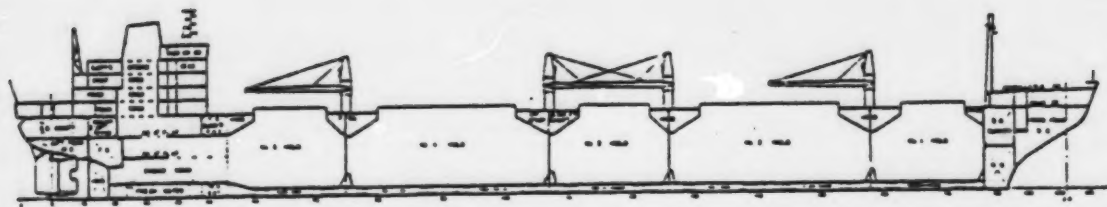


Part 3 (Cont'd)

G ARRANGEMENT & PROFILE

FIG. 7

TYPICAL ICEBREAKING CARGO VESSEL



GERMAN & MILNE INC.
NAVAL ARCHITECTS

LAKE MELVILLE/OFFSHORE LABRADOR YEAR-ROUND

NAVIGATION STUDY, 1978-79

APPENDIX C

FIELD PROGRAM REPORTS

(NORDCO Limited, REMOTEC Applications Inc., and FENCO (Nfld.) Limited)



APPENDIX C.1

January Field Program (NORDCO Limited and Remotec Applications Inc.)

C.1 JANUARY FIELD PROGRAM (NORDCO Limited and Remotec applications Inc.)

C.1.1 Introduction

During the winter of 1979, a field program was conducted on Lake Melville as a part of the Lake Melville/Offshore Labrador Transportation Study. The purpose of the field program was to gather data on the ice conditions in Lake Melville specifically in areas of significant ridging and rafting in the eastern end of the lake. In addition data were to be collected on the properties of the ice such as strength, salinity and temperature and a continuous record of meteorological conditions was to be made in an attempt to relate ice events to such conditions. Personnel from NORDCO Limited, Remotec Applications Inc. and Fenco (Nfld.) Limited participated in the program.

C.1.2 Preliminary Reconnaissance

A preliminary ice reconnaissance flight was conducted over Lake Melville on December 9, 1978 to assess the severity of ridging along the Lake especially in the constricted channels at the eastern end of the Lake. The initial leg of the flight was along the southern shore of the Lake, with the return flight from Rigolet paralleling the northern shore. There was no indication of heavy ridging on the inter-island channels nor on the main body of Lake Melville. Two ice thickness measurements of 0.40 m were recorded to the east of Gull Island. Two further thicknesses of 0.34 m and 0.37 m were recorded in the remnant of a ship's track, which was located in the same general area. This track was relocated during a reconnaissance flight on January 29, 1979

and is plotted on the accompanying charts from that day. A more complete description of the preliminary ice reconnaissance of December 9, 1978 is given in Section C.1.6.

C.1.3 Field Program

The field program on Lake Melville was conducted between January 16 and February 3, 1979. During a large portion of this period, unusually high temperatures were experienced and this resulted in less than ideal conditions on the ice for efficiently conducting the tests. In addition, because of poor flying conditions at Goose Bay, the use of helicopters in conducting the tests was somewhat limited. However, a number of ice thickness measurements were made in critical areas, and measurements of salinity and temperature and strengths of a number of ice samples were taken.

In general, temperatures during the period January 16-19 were in the -30°C range with light winds, except on January 16. The temperature rose to -1°C in the evening during January 29, but dropped again to -14°C on January 21. Air temperature increased substantially on January 22 reaching $+4^{\circ}\text{C}$. Temperatures then remained above 0°C for the duration of the field trip. This was most unusual for the time of year and the area. January mean daily temperature normal for Goose Bay is approximately -15°C . Snow began falling on the afternoon of January 19 and new snow accumulation of 0.25 m was measured on the morning of January 20. The new snow density equaled 0.048 cm^3 . The warming trend experienced on January 22 brought with it high winds, gusting to 25 m/sec (55 mph), and

heavy rain. As a result of these conditions, there was no snow remaining on the ice on the morning of January 23. The ice surface was intermittently covered with the melt-water ponds up to 0.15 m in depth. These conditions persisted throughout the remainder of the period, except on occasions when a light skim of ice (1-2 cm) formed on the meltponds. Relative humidity generally remained high during the period due to the water on the ice and the prevailing high temperatures. Wind speeds near Cabot Island were mainly less than 10 m/sec. and prevailed from the northeast to southeast. Cloud ceiling was generally 600-1200 m (2000-4000 ft) and the weather was suitable for flying at most times. However, this was not the case at Goose Bay.

C.1.4 Data Collected

The data collected during the field trip is broken down into the following sections:

- i) Meteorological data
- ii) Ice character data
- iii) Ice reconnaissance data
- iv) Photographic data

Meteorological Data

A Stevenson screen and thermo-hydrograph were set up 100 metres to the south of base camp on Cabot Island (53°43'N, 59°08'24"W). The site was well exposed with the base of the screen approximately 1.5 m above the ice surface.

Synoptic weather observations were made at this site, when possible, at 0800, 1100, 1400, 1700, 2000 and 2300 hours LST (1200, 1500, 1800, 2100, 2400, 0300 hours GMT). These data are presented for the period 1400 LST January 21, 1979 to 0800 LST January 31, 1979 in Section 3.1.7, Table 1. The measurements were made with the following instruments:

Dry Bulb Temperature	Laubrecht sling psychrometer using average of both thermometers
Relative Humidity	Laubrecht recording thermohygrograph with wetted hair type element
Wind Speed	Lambrecht hand-held anemometer calibrated in meters/sec.
Barometric Pressure	Negretti and Zamba MK2 Precision Aneroid Barometer (non-recording)
Sky Condition	Visually, using mountains to south east as 600 m (2000 ft) reference

In addition to relative humidity, dry bulb temperature was continually recorded on the thermo-hygrograph during the period. Also a Lambrecht chart barograph continuously recorded barometric pressure at the base camp. Temperature, relative humidity and barometric pressure from chart recordings, and wind speed from synoptic observations are shown graphically in Figure C.1.1.

A second weather station was established at a site 12 km (7.5 statute miles) due north from Cabot Island. This station was of the automatic type (AANDERAA) with recordings being made from 12 channels on magnetic tape at 20 minute intervals.

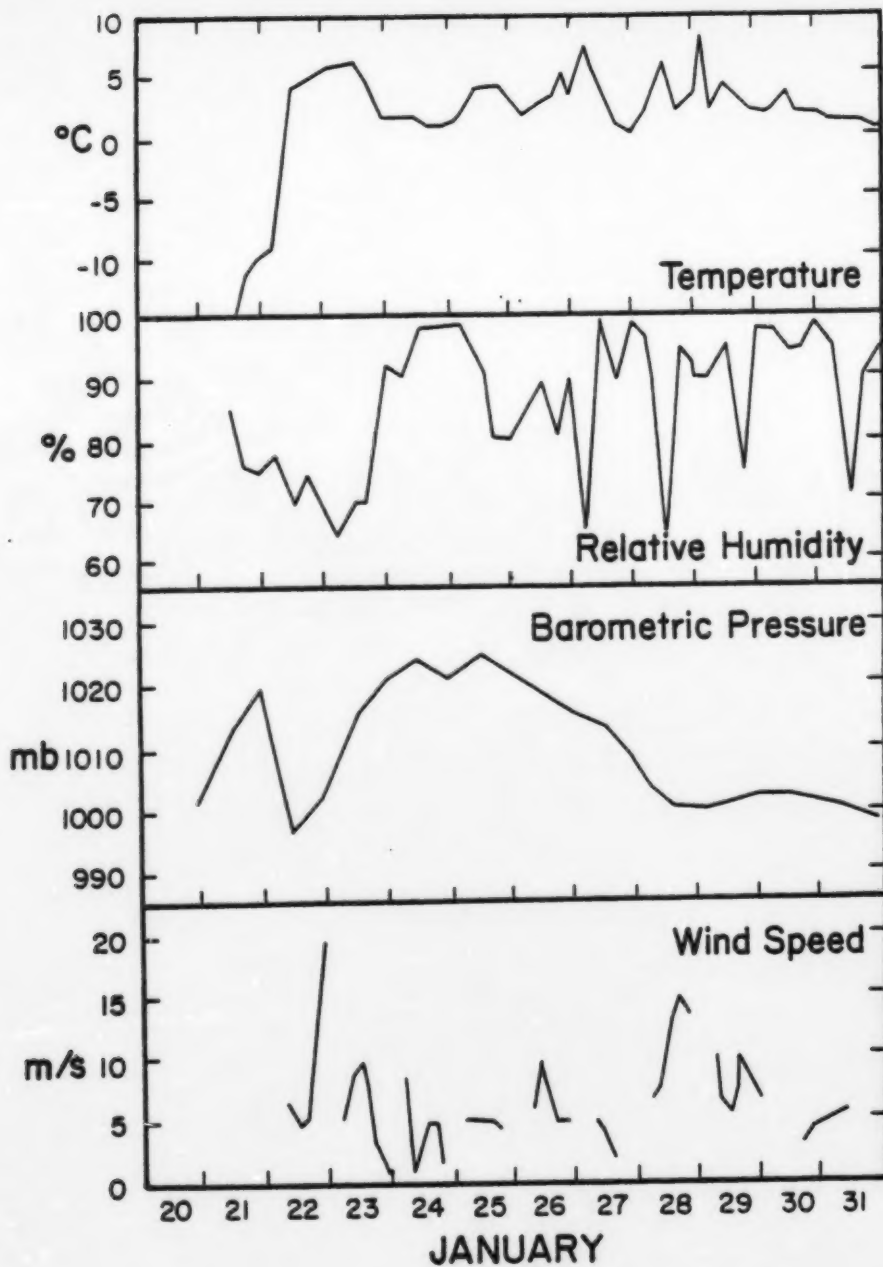


FIGURE C II METEOROLOGICAL DATA FOR JANUARY, 1979

The following meteorological parameters were measured:

- wind speed average (over 20 minute interval)
- wind speed maximum (over 20 minute interval)
- wind direction
- dry bulb temperature
- relative humidity

A barometric pressure sensor was installed on this weather station during mid-March, when a trip was made to Lake Melville to change the recording tape and fly a reconnaissance of the Lake. The battery in the unit was also replaced at this time.

Ice Character Data

Ice thickness measurements were made between St. John Island and Green Island. Measurements were also made northward from the automatic weather station located 12 km north of Cabot Island. The ice thickness stations are shown on the map of Figure C.1.2. Ice thickness data are presented in Section C.1.7, Table 2.

Cores were taken through the ice sheet at 1.6 km intervals, while ice thicknesses were measured at 0.3 km intervals. Ice core interval temperatures were measured at 0.2 m intervals, the core then being sectioned (roughly 0.2 m). Each section of the 0.15 m diameter core was placed in a container for later salinity analysis. The core hole was then used for bore hole strength tests. Two 30 ml samples from the meltwater of each core section were analysed by titration for salinity. These

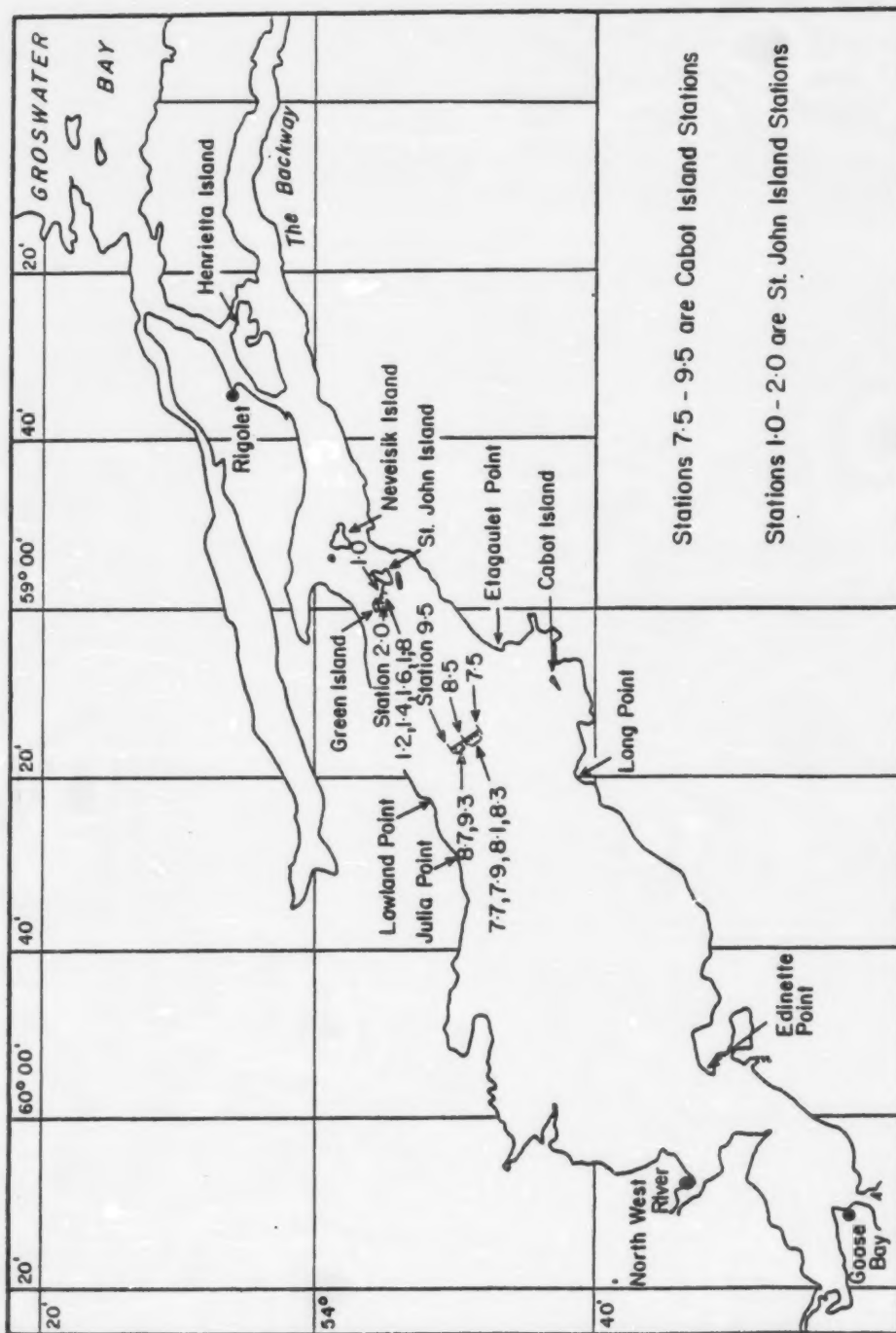


FIGURE C1.2 STATION LOCATIONS

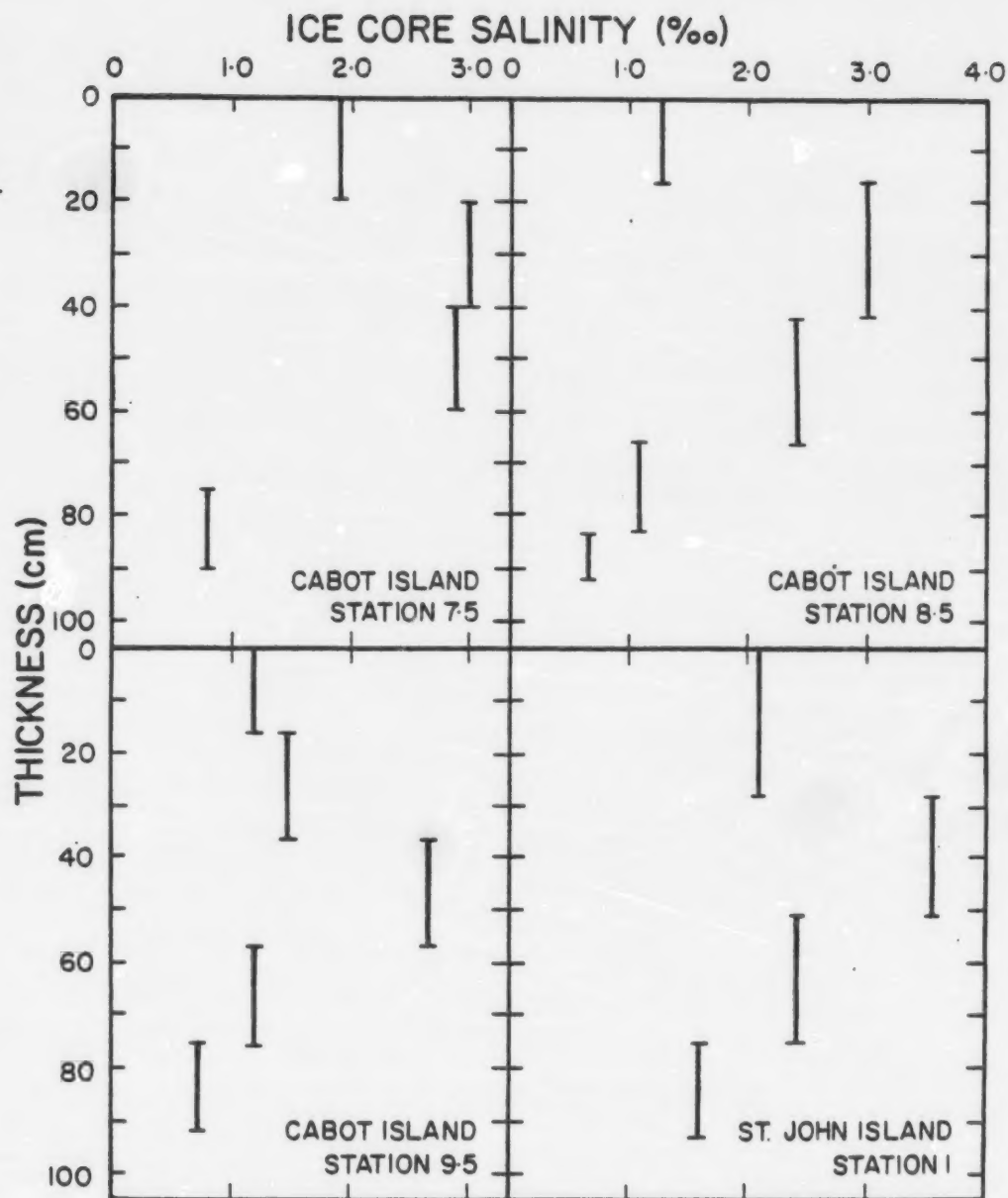


FIGURE C1.3 VARIATIONS IN SALINITIES WITH DEPTH OF CORES FROM FOUR LOCATIONS

data are presented in Section C.1.7, Figure C.1.3. Confined compressive ice strength and core temperature profiles have been reported by FENCO Limited and are included as Section C.2.

Ice Reconnaissance - January 31, 1979

A helicopter reconnaissance of the entire Lake from Goose Bay to Rigolet was made on January 31, 1979. Many of the ice features shown would not be visible if snow cover was present. Thus, this information should be beneficial in the interpretation of SAR imagery, since radar signals may penetrate snow cover.

In general the ice was mainly smooth with many melt ponds. Sastrugi (sharp, irregular ridges formed on a snow surface by wind and erosion, generally parallel to the direction of prevailing wind at the time they were formed) were most prominent in the western portion of the lake.

Ridging on the Lake was not extensive. The most intensive ridging was to the west and southwest of Green Island and to the west and southwest of the southwest point of St. John Island. Snow accumulations were greatest on the channel to the east of St. John Island. Thermal ridges were the typical type found in ice cover on the western end while rafted ice (0.15 m pan thickness) and thermal ridges were seen in the exposed eastern end of the Lake.

C.1.5 Field Trip Discussion

The Lake Melville area experienced an unusually mild period during this field trip. This, coupled with a higher number of days when the helicopter could not leave Goose Bay due to flying conditions, resulted in travelling difficulties to which there was no solution. The amount of data collected on ice sheet conditions was thus limited.

The graphs presented in Figure C.1.1 and synoptic observations in Section C.1.6 show the meteorological conditions during the period. Table 3 shows the days on which the helicopter or aircraft was able to leave Goose Bay. Also illustrated are the days which were suitable for flying in the vicinity of Cabot Island (300 m (1000 ft), 0.8 km (0.5 mile) visibility). As can be seen, the helicopter was unable to leave Goose Bay on most days during the critical portion of the field trip. Weather during daylight hours in the vicinity of Cabot Island was suitable for flying on all but one day. In future, it is recommended that the helicopter be stationed at the base camp.

Travel by snowmobile was limited to speeds of 16-24 kph. The round trip to St. John Island took approximately 4 hours. On one day, when weather and ice conditions were particularly poor, the trip took 6 hours return. If the helicopter had been able to reach Cabot Island on a daily basis, this problem would have been all but eliminated, and better coverage of the entire Lake would have been obtained. Due to the mild weather and precipitation the ice surface was generally wet and slick, offering little friction for the snowmobile track.

TABLE 1

METEOROLOGICAL CONDITIONS

C.1.6

Date (LST)	Time (LST)	Dry Bulb (°C)	R.H. (%)	Wind Speed (m/s)	Wind Dir. (Nmag)	Barometric Pressure (mb.)	Sky Condition (cloud height cover, type)	Precip.
Jan 21	1400			C		1016.8	E45 SCT SC2	
	1700			C		1019.4	E40 BKN AC9	
	2000	-14.0		C		1020.5	No stars visible	
	2300	-4.6	76	C			No stars visible	
Jan 22	0800	-4.6		C		1014.2	10 OVC ST10	
	1100	3.2	68	7	NE	1011.1	20 BKN SC8	
	1400	4.0	68	4	NE	1008.2	20 BKN SC6, E60 BKN AC3	
	1700	3.8	70	6	NE	1005.1	20 OV6 ST10	
Jan 23	2000	-1.6	80	12	SE	1003.5	No stars visible	R--
	2300			20G25	SE	997.9	No stars visible	R+
	0800	4.4	74	5	E	1002.4	20 BKN ST9	
	1100	5.8	69	8G12	E	1003.7	20 OVC ST10	
Jan 24	1400	6.2	68	10G15	SE	1005.2	30 SCT ST4, E40 BKN AS4, E90 OVC CS2	
	1700	3.6	77	6	NE	1009.4	30 SCT SC3	
	2000	1.1	93	3G5	N	1012.9	E40 BKN SC9	
	2300	1.6	90	1	N	1016.1	E50 SCT AC4	
Jan 25	0800	0.9	94	8	NE	1022.7	20 OVC ST10	
	1100	1.0	97	1	N	1022.3	5 OVC ST10 X	
	1400	1.5	97	5	NE	1022.0	5 OVC ST10 X	
	1700	1.2	98	5	NE	1023.0	5 OVC ST10 X	
Jan 26	2000	1.2	98	2	N	1024.4	No stars visible	
	2300	1.2	98	C		1024.9	No stars visible	
	0800	2.2	94	5	NE	1023.6	50 BKN AC8, E10 BKN CI1	
	1100	2.4	90	C		1023.5	50 BKN AC9	
Jan 27	1400	N/A	N/A	N/A	N/A	N/A	N/A	
	1700	4.2	79	5	NE	1025.1	30 BKN SC8 E50 OVC AS2	

Date (LST)	Time (LST)	Dry Bulb (°C)	R.H. (%)	Wind Speed (m/s)	Wind Dir. (Nmag)	Barometric Pressure (mb.)	Sky Condition (cloud height cover, type	Precip.
Jan 26	2000	4.0	70	4	SE	1026.3	No stars visible	
	2300	1.2	80	4	E	1025.6	Stars visible 7/10 cover	
	0800	1.0	85	6	NE	1023.8	40 BKN SC6 60 BKN AC2	
	1100	0.8	95	9	NW	1023.6	40 BKN SC8 E100 BKN CI1	
	1400	N/A	N/A	N/A	N/A	N/A	N/A	
	1700	1.5	90	5	NE	1020.8	30 BKN SC8	
	2000	3.8	84	5	NE	1020.2	Stars visible 8/10 cover	
Jan 27	2300	5.2	76	5	E	1019.1	30 BKN SC8	
	0800	N/A	N/A	N/A	N/A	N/A	N/A	
	1100	3.0	90	5	NE	1017.7	60 SCT AC5	
	1400	N/A	N/A	N/A	N/A	N/A	N/A	
	1700	2.6	78	2	NE	1015.5	40 SCT SC1 E70 BKN AC6	
	2000	0.5	97	C		1015.5	Stars visible 2/10 cover	
Jan 28	2300	N/A	N/A	N/A	N/A	N/A	N/A	
	0800	1.0	92	7	NE	1010.4	30 BKN SC6 E60 BKN AC2	
	1100	1.2	91	8	NE	1009.3	30 SCT SC5 E60 BKN AC3	
	1400	N/A	N/A	N/A	N/A	N/A	N/A	
	1700	1.4	94	15	NE	1004.8	E40 OVC SC10	
	2000	1.2	90	13G16	NE	1003.4	No stars visible	
Jan 29	2300	N/A	N/A	N/A	N/A	N/A	N/A	
	0800	1.6	97	10	NE	999.8	30 BKN SC8 E60 OVC AC2	

Date (LST)	Time (LST)	Dry Bulb (°C)	P.H. (%)	Wind Speed (m/s)	Wind Dir. (Nnag)	Barometric Pressure (mb.)	Sky Condition (cloud height cover, type)	Precip.
Jan 30	1100	1.0	97	7	NE	1000.5	30 BKN SC8 E60 BKN AC1	
	1400	3.8	87	5	NE	1000.0	30 SCT SC2 E70 BKN AC7	
	1700	1.6	89	10	NE	1001.5	No stars visible	
	2000	1.8	95	7	NE	1001.4	No stars visible	
	2300	N/A	N/A	N/A	N/A	N/A	N/A	
	0800	0.6	98	C		1004.4	30 SCT SC1 E60 SCT AC2 E90 BKN CI4	
	1100	1.8	95	C		1004.4	30 BKN SC8	
	1400	2.2	94	C		N/A	30 SCT SC2 E60 BKN AC4	
	1700	0.9	98	3	NE	1003.7	30 SCT SC5	
	2000	1.8	98	4	NE	1003.6	No stars visible	
Jan 31	2300	N/A	N/A	N/A	N/A	N/A	N/A	
	0800	0.1	80	6	NE	1003.0	40 SCT SC3	

TABLE 2
ICE THICKNESS MEASUREMENTS

Station		Ice Thickness (m)	Freeboard (m)	Snow Thickness (m)	Comments
Cabot Island	7.5	0.84	0.06	0.0	
Cabot Island	7.7	0.58	0.10	0.10	Infrequent Snow Patches.
	7.9	0.79	0.0	0.10	Slush, infrequent snow patches
	8.1	1.02	0.07	N/A	Snow, slush, water on ice; infrequent, light ridges
	8.3	0.90	0.07	0.0	
	8.5	0.91	0.07	N/A	Scattered snow patches
	8.7	0.90	0.06	N/A	Infrequent snow patches
	9.3	2.20+	N/A		Light ridges, ice cover not drilled through
	9.5	0.92	N/A	N/A	
St. John	1.0	0.92	0.06	0.10	Light ridges up to 50 cm high frequency 3 miles.
	1.4	0.92	0.08	0.0	
	1.6	0.93	0.07	0.0	
	1.8	0.91	0.09	0.0	
	2.0	0.86	0.06	0.0	

TABLE 3

	GOOSE BAY		CABOT ISLAND	
	Fly	No Fly	Fly	No Fly
January 16		x	N/A	N/A
January 17	x		x	
January 18	x		x	
January 19	x		x	
January 20		x	x	
January 21	x		x	
January 22		x	x	
January 23		x	x	
January 24		x		x
January 25		x	x	
January 26	x		x	
January 27		x	x	
January 28		x	x	
January 29		x	x	
January 30	x		x	
January 31	x		x	
February 1 (helicop)	x	x (aircraft)	x	
February 2	x		x	

APPENDIX C.2

Ice Strength Measurements and Calculations

Submitted to: NORDCO Limited

Submitted by: FENCO (Nfld.) Limited

1. INTRODUCTION

The seasonal ice cover combined with a sub-arctic climate complicate the planning and design of activities in Lake Melville.

The ice cover generally reaches an undeformed thickness of approximately 1.0 m. During and shortly after the period of freeze-up, the ice cover is susceptible to rafting and ridging by wind and wave action.

The purpose of this study was to study and gather basic strength and mechanical properties of the ice cover found on Lake Melville.

2. STUDY AREA

Ice tests were conducted in the area of Cabot Island and in the area of St. John Island in Lake Melville.

The actual locations were as follows:

- Cabot Island:

On a line, from Cabot Island heading due north, tests were conducted at 7.5, 8.5 and 9.5 miles from Cabot Island.

- St. John Island:

On a line, from St. John Island heading to Green Island, tests were conducted at 1.0 miles from St. John Island.

The climate of this area is highly variable with strong winds, snow, fog and freezing rain. This greatly reduces the number of days available for site investigations. From past experiences these conditions must be expected during the periods of future ice surveys.

3. DESCRIPTION OF PROGRAM AND TESTING METHODS

The object of this study was to gather strength information on the ice cover on Lake Melville. Data were collected on ice strength, temperature, salinity and thickness.

A summary of tests and measurements performed by FENCO (NFLD.) LTD. is given below.

3.1 Ice Strength

Measurements of confined compressive strength were obtained at the study locations. These tests have also been performed at other sites throughout the Arctic and sub-Arctic using methods and equipment developed by FENCO. The advantage is that they are small scale tests, easily performed on site with a minimum disturbance to the ice.

3.2 Confined Compressive Strength

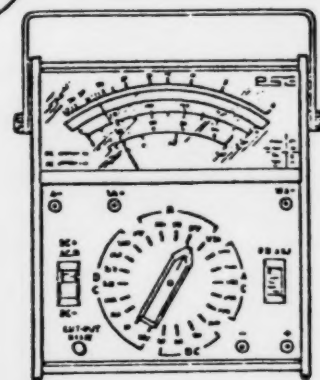
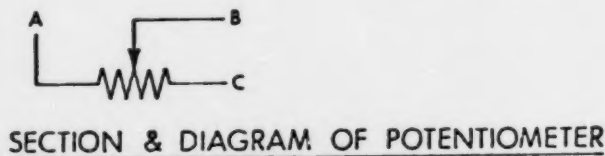
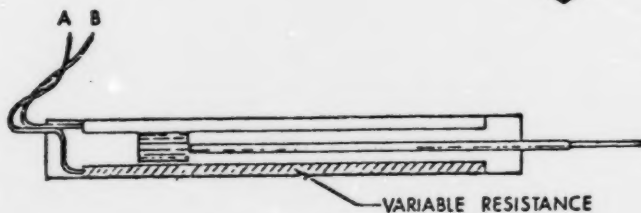
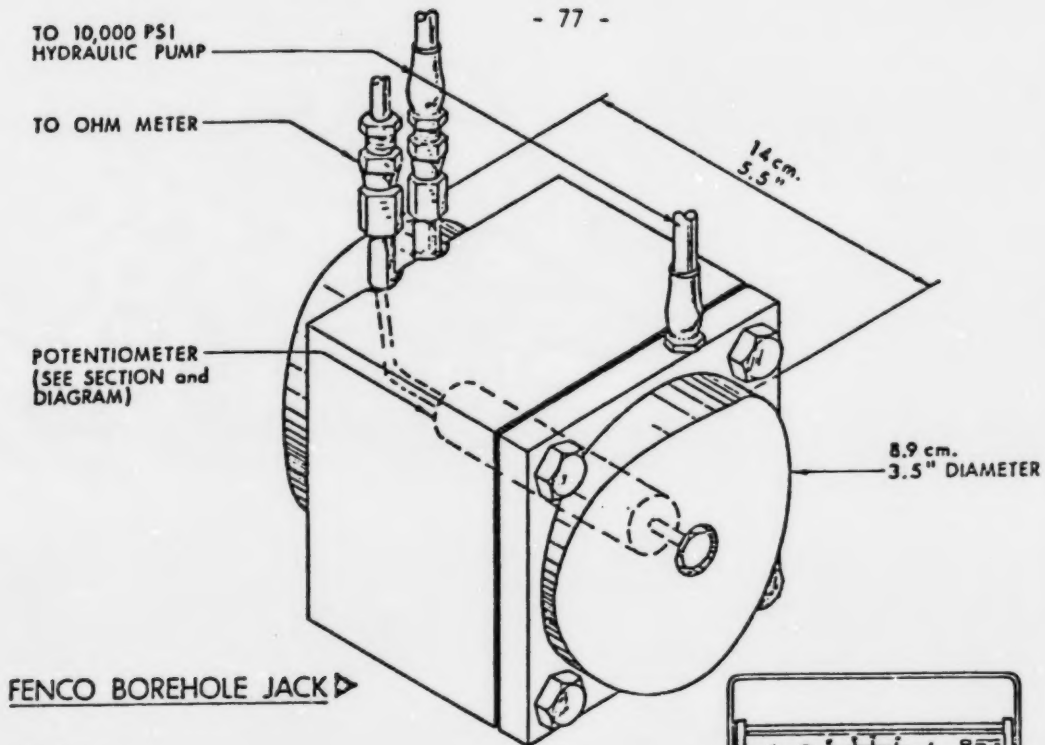
Borehole compression tests are usually the quickest and most reliable test which can be performed in many naturally occurring materials and this is what FENCO has commonly used for ice.

For the purpose of this test, a 15 cm diameter hole is drilled in the ice. A borehole compression testing jack developed by FENCO is then lowered into the hole and tests are conducted on the sides of the hole at .3 m intervals. A diagram of the jack is presented in Figure 3.2.1. Hydraulic pressure is applied to the piston located inside the jack body by a pump on the ice surface. Oil is transferred from the pump to the pressure cylinder by means of high pressure hydraulic hose supplied with quick disconnect couplings. Displacement is measured using a linear, variable resistor mounted on the jack body with the plunger attached to the front plate. Pressure readings are converted to electrical signals using a transducer and this plus the displacement information are then plotted on an X-Y plotter during the test, providing instantaneous, visual output.

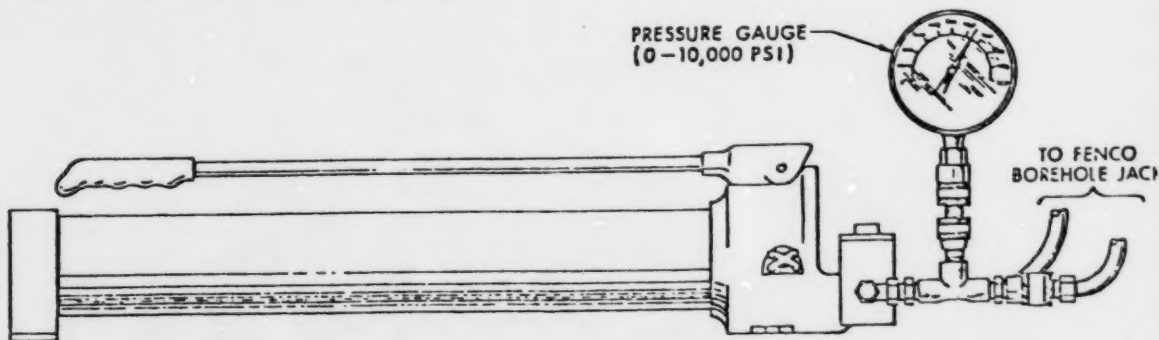
After the jack is lowered into the hole and the test begun, the stress situation is as shown in Figure 3.2.2. The major principal stress σ_1 , is the applied plate pressure. Since the pressure is being applied to what is essentially the surface of a semi-infinite solid, the stresses are three dimensional. At the beginning of the test, a bulb of crushed ice forms beneath the load plates because of surface unevenness and high local stress concentrations. This bulb is confined by stresses σ_1 , σ_2 , and σ_3 as shown in Figure 3.2.2. The bulb of crushed ice continues to grow as the applied pressure is increased until at some point is pushed out around the load plate and failure is reached. In many cases the crushed ice never escapes from the bulb but the size of the bulb diameter grows larger and larger and the displacement increments increase exponentially. Some of the ice near the load plate re-crystallizes from the high pressure. Large displacements are associated with this consolidation and the plotting of pressure displacement curves enables one to determine the "ultimate" or confined compressive strength of the ice since the curve approaches this value asymptotically.

3.3 Elastic Modulus

Elastic modulus values for the ice are determined from the pressure-deflection curves of the borehole tests. The analysis gives much useful information regarding the relative brittleness and ductility of the ice throughout its depth. If it is assumed that the bulb of crushed material behaves as a Mohr-Coulomb material with cohesion equal to 0 and friction angle ϕ , then a pressure-

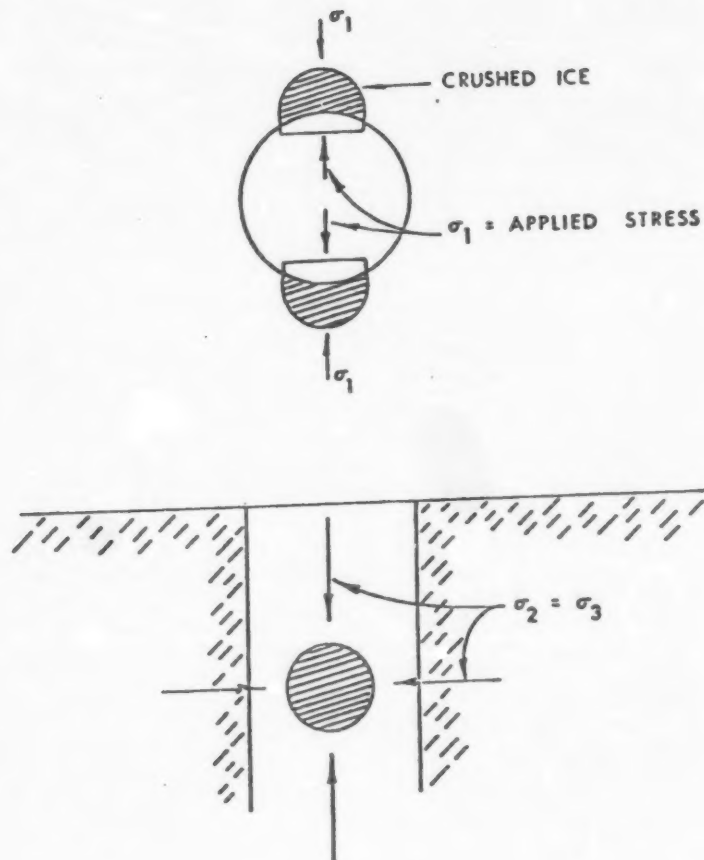


OHM METER



10,000 PSI HYDRAULIC PUMP

BOREHOLE JACK
FIGURE 3.2.1



PRINCIPAL STRESSES FOR CONFINED COMPRESSIVE STRENGTH TEST
FIGURE 3.2.2

displacement relationship can be written from equilibrium and compatibility considerations.

The equation is:

$$\delta = \frac{D\sigma_{uc}}{nE} (1+\mu) \left[\frac{np}{2\sigma_{uc}} \right]^{3\beta}$$

where:

δ = Plate deflection measured during the test.

p = Pressure applied to the plate via the hydraulic jack.

D = Plate diameter (90.6 mm).

E = Elastic modulus of the uncrushed ice.

n = Ratio of ice unconfined compressive strength to uniaxial tensile strength (usually taken as 3).

μ = Poisson's ratio (0.2).

σ_{uc} = Unconfined compressive strength of the ice.

$$\beta = \frac{1 + \sin \phi}{4 \sin \phi}$$

ϕ = Friction angle of the crushed ice (35°).

Theoretical pressure deflection curves are plotted using this equation for various elastic modulus values and are then compared to the curves plotted from field data (Figure 3.3.1). The theoretical curve best fitting the measured one determines the elastic modulus of the ice at that depth.

3.4 Flexural Strength

Using the results of the Borehole Jack tests (i.e. confined compressive strength) we can determine the Flexural strength of the ice from:

$$\frac{\sigma_c}{\sigma_{uc}} = \frac{3}{1}$$

$$\frac{\sigma_{uc}}{\sigma_f} = \frac{3}{1}$$

therefore:

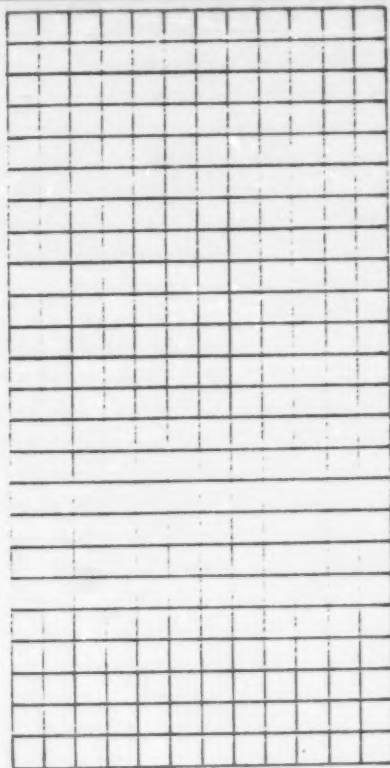
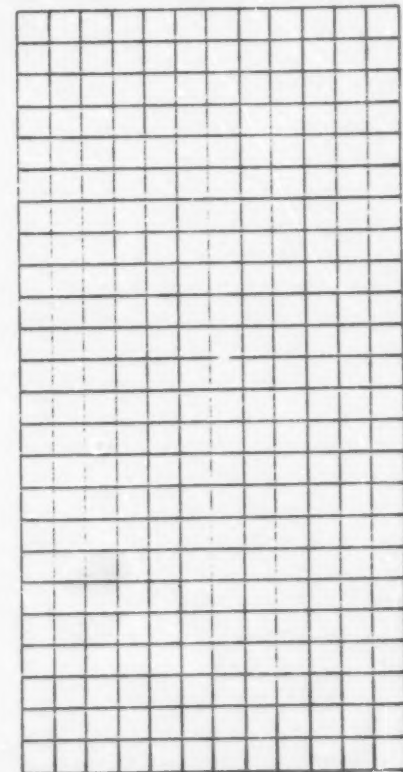
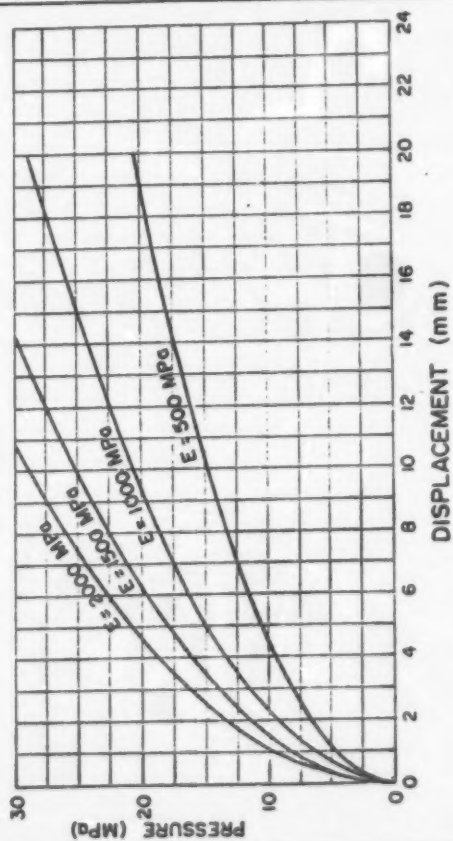
FIG. 3.3.1

FENCO BOREHOLE JACK
THEORETICAL PRESSURE - DISPLACEMENT
CURVES FOR DIFFERENT E VALUES

$$S = \frac{D\sigma_c}{nE} (1 + \mu) \left[\frac{nP}{2\sigma_c} \right]^{3/8}$$

$$B = \frac{1 + \sin \phi}{4 \sin \phi}$$

$$\phi = 35^\circ$$



$$\frac{\sigma_c}{\sigma_f} = \frac{9}{1}$$

where:

σ_c = confined compressive strength (borehole strength)

σ_{uc} = unconfined compressive strength (flaking strength)

σ_f = flexural strength

3.5 Temperature

Through the use of a 15 cm ϕ corebarrel remodelled by FENCO, ice cores were taken at many of the sites visited. A small hole was drilled at intervals along these cores and a temperature probe inserted. Temperature readings taken were accurate to $\pm 0.1^\circ\text{C}$. This is the only practical means of obtaining ice temperatures when a single short term visit is planned.

3.6 Salinity

After determining the temperatures, the cores were cut into roughly 25 cm lengths and placed in appropriately labelled plastic bottles fitted with screw on caps. The use of these sample bottles greatly reduces any evaporation and loss of the ice sample. These samples were transported to the base camp where they were allowed to melt. A YSI conductivity bridge was used to determine the salinities of these ice samples. Although the bridge is accurate to $\pm 0.07\%$ of the reading, brine may drain from the cores during drilling, and while the cores are lying on the ice, thus reducing the accuracy of the resulting salinities. The total error in these measurements is estimated to be approximately 0.50 o/oo.

3.7 Ice Thickness

Ice thicknesses were obtained by drilling holes in the ice with a 15 cm ϕ hand auger. Hole depths were measured with a tape. Thicknesses were also taken in ice core holes.

3.8 Brine Volume

Brine volume (μb) was found by using the values of temperature and salinity in Frankenstein and Gerner's equation (1967):

$$\mu_b = S_i \times 10^{-3} \left[\frac{-49.185}{\theta_i} + 0.532 \right]$$

where:

μ_b = brine volume 0/00

S_i = salinity 0/00

θ_i = temperature °C ($-0.5 \leq \theta_i \leq -22.9$ °C)

4. RESULTS AND DATA SYNTHESIS

4.1 General

The function of this program was to study the strength and mechanical properties of the ice cover on Lake Melville during the latter part of January 1979. Mean values of ice mechanical properties are presented in table 4.1.

4.2 Confined Compressive Strength

The basic strength data collected during this survey are presented in Appendix I.

The confined compressive strengths ranged from 9.6 MPa to 16.5 MPa with a mean value of 11.8 MPa.

The strength properties are presented in tables 4.2 to 4.5 and are plotted in Figures 4.1 to 4.4.

4.3 Ice Stiffness

The calculated E values ranged from 500 MPa to 1500 MPa with a mean value of 660 MPa. The E values are presented in tables 4.2 to 4.5.

4.4 Flexural Strength

The calculated flexural strengths ranged from 1.1 MPa to 1.8 MPa with a mean value of 1.3 MPa. These values generally seem to be in agreement with those reported by MUN (1973). Flexural strengths are presented in tables 4.2 to 4.5.

4.5 Ice Temperature

From the temperature profiles of the ice cover the ice temperature ranged from $+0.8^{\circ}\text{C}$ to -1.8°C with a mean value of -0.85°C .

The air temperatures at the ice surface ranged from $+0.3^{\circ}\text{C}$ to $+1.8^{\circ}\text{C}$ with a mean value of 1.0°C .

Temperatures are presented in tables 4.2 to 4.5 and are plotted in Figures 4.1 to 4.4.

4.6 Salinity

From the Salinity profiles the salinities ranged from $0.7^{\circ}/\text{oo}$ to $3.4^{\circ}/\text{oo}$ with a mean value of $1.8^{\circ}/\text{oo}$. The highest salinities found were at St. John Island 1.0 . The salinities from the Cabot Island line decreased from station 7.5 to station 9.5.

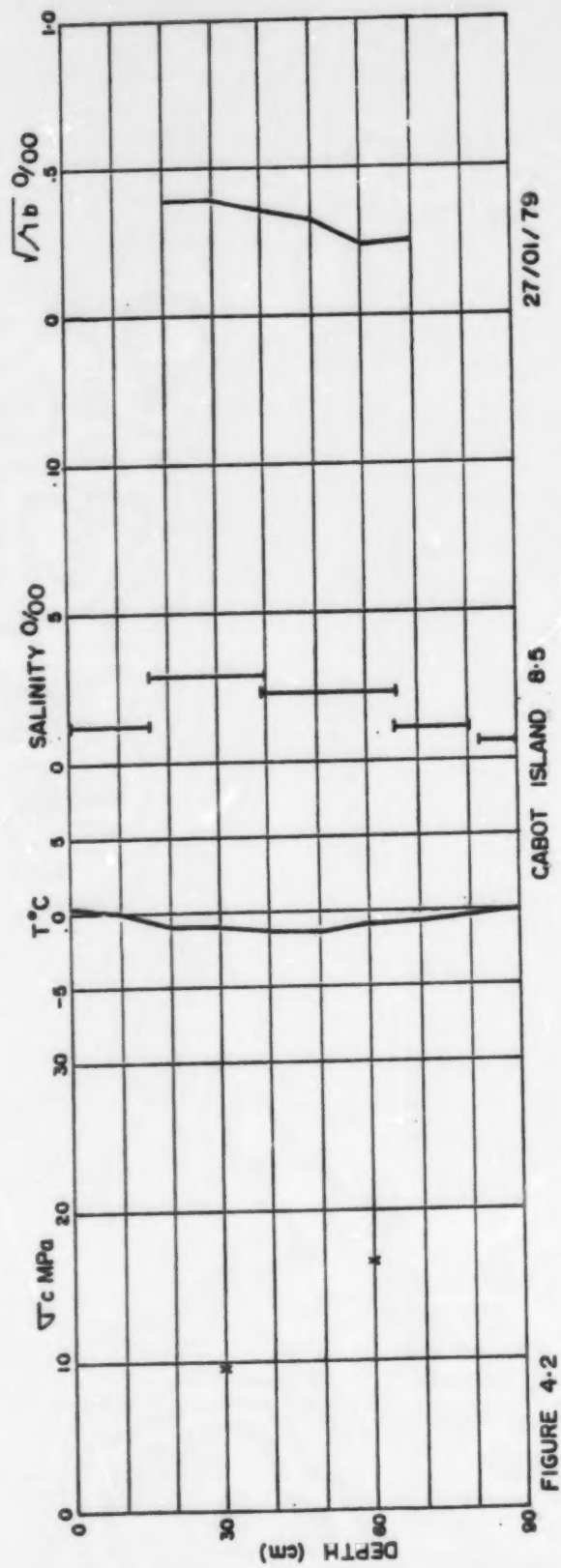
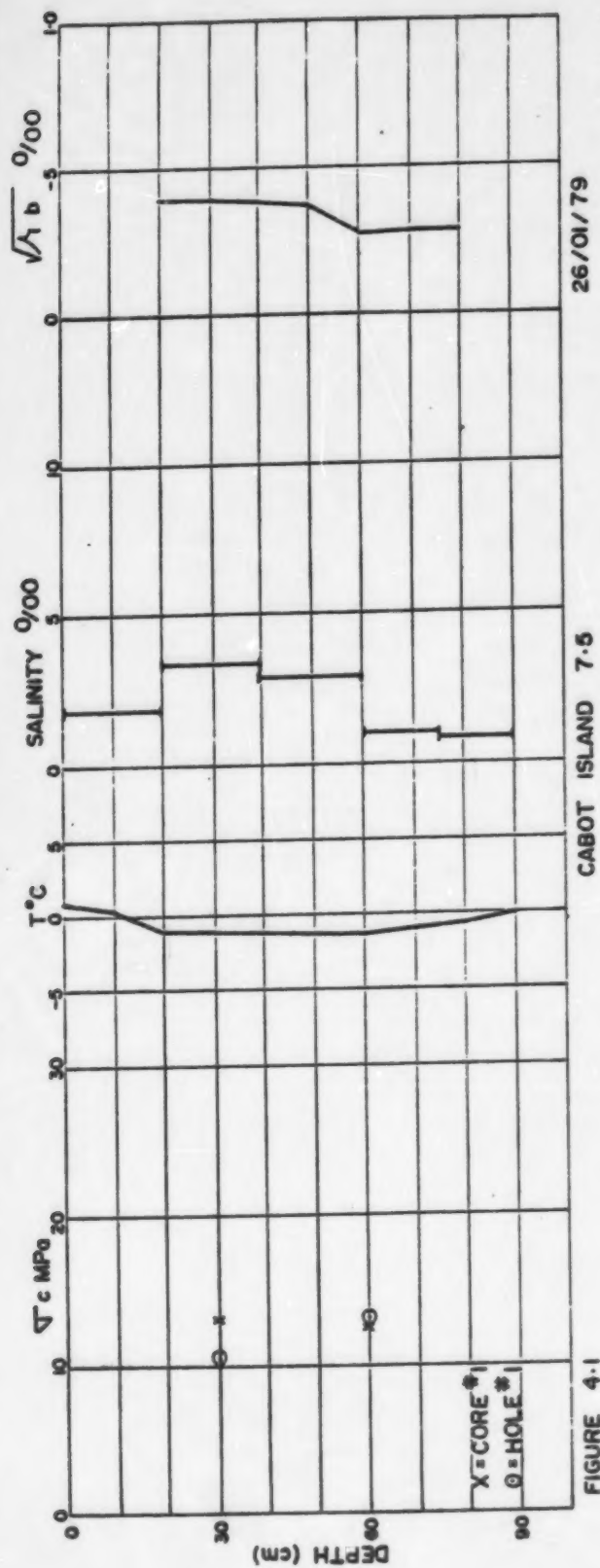
Salinity values are presented in tables 4.2 to 4.5 and are plotted in Figures 4.1 to 4.4.

4.7 Ice Thickness

Ice thickness from four core holes ranged from 85 cm to 93 cm with a mean of 90.5 cm. Thicknesses are presented in tables 4.2 to 4.5.

4.8 Brine Volumes

From the calculations of brine volume the values ranged from $0.20^{\circ}/\text{oo}$ to $0.39^{\circ}/\text{oo}$ with a mean value of $0.31^{\circ}/\text{oo}$. Brine volumes are presented in tables 4.2 to 4.5 and are plotted in Figures 4.1 to 4.4.



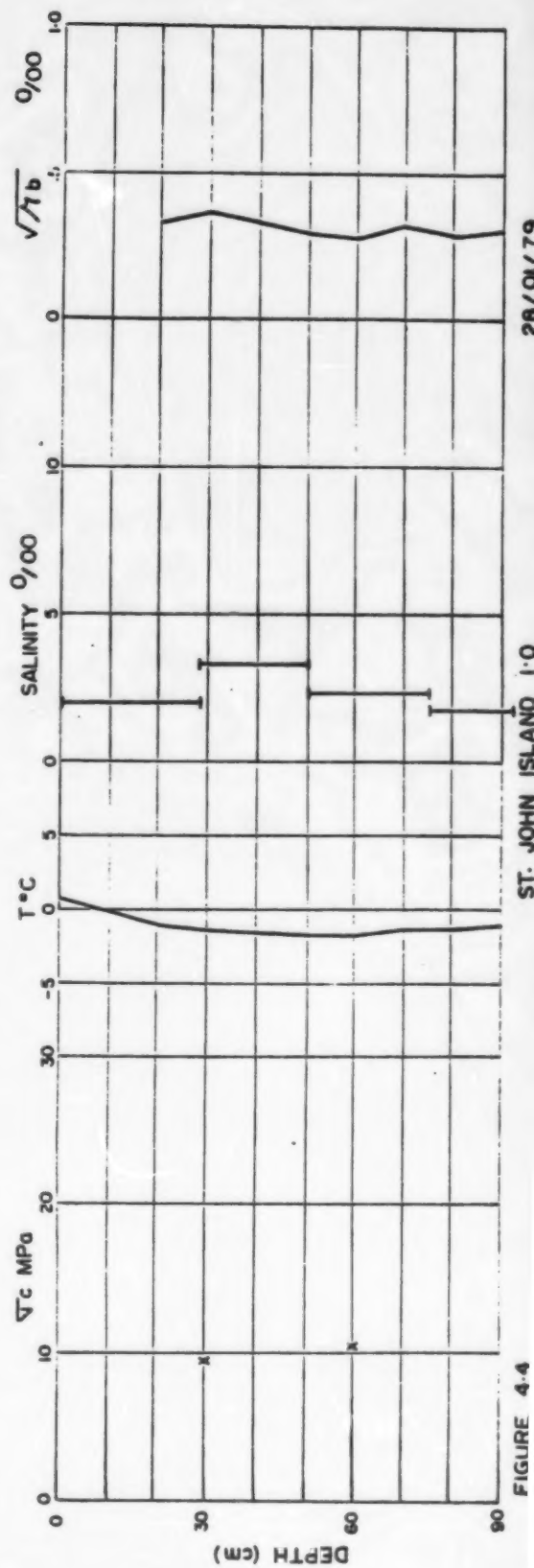
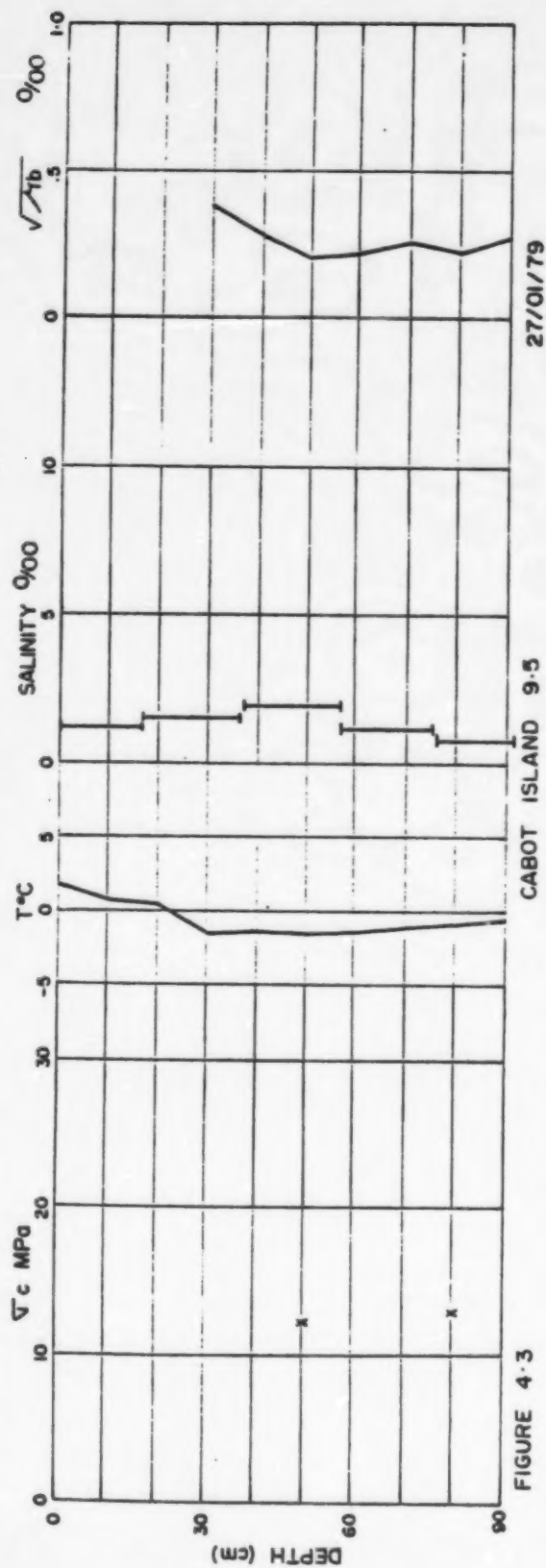


TABLE 4.1
MEAN VALUES OF ICE MECHANICAL PROPERTIES

Parameter	Location			
	C.I. 7.5	C.I. 8.5	C.I. 9.5	ST.J.I. 1.0
Temperature (°C)	-0.7	-0.7	-0.8	-1.2
Salinity (0/00)	1.9	1.7	1.3	2.4
$\sqrt{\text{Brine Volume (0/00)}}$	0.34	0.32	0.26	0.31
Confined Compressive Strength (MPa)	12.2	13.1	12.6	9.9
Flexural Strength (Calculated) (MPa)	1.4	1.5	1.4	1.1
Elastic Modulus (MPa)	563	1000	625	583

TABLE 4.2
BASIC ICE PROPERTIES FOR CABOT ISLAND 7.5

DEPTH (CM)	T (°C)	DEPTH OF CORE (CM)	S (0/00)	σ_c (MPa)	σ_f (MPa)	E (MPa)	$\sqrt{\mu b}$ (0/00)
10	+0.3	0 - 20	1.9				N/A
20	-1.0	20 - 40	3.0				0.39
30	-1.0			13.0	1.4	500	0.39
40	-1.0	40 - 60	2.9				0.38
50	-1.1						0.36
60	-1.1	60 - 75	1.0	12.6	1.4	750	0.27
70	-0.9	75 - 90	0.8				0.28
80	-0.5						0.28
90	0.0						N/A
MEAN	-0.7		1.9	12.8	1.4	563	0.34

Ice Thickness = 85 cm

Air Temperature = + 1.0°C

TABLE 4.3
BASIC ICE PROPERTIES FOR CABOT ISLAND 8.5

DEPTH (CM)	T (°C)	DEPTH OF CORE (CM)	S (0/00)	σ_c (MPa)	σ_f (MPa)	E (MPa)	$\sqrt{\mu b}$ (0/00)
10	0.0	0 - 17	1.2				N/A
20	-1.0	17 - 42	2.9				0.38
30	-1.0			9.6	1.1	500	0.38
40	-1.1	42 - 66	2.4				0.35
50	-1.2						0.32
60	-1.0	66 - 83	1.1	16.5	1.8	1500	0.24
70	-0.9						0.25
80	-0.4	83 - 92	0.7				N/A
90	-0.1						N/A
MEAN	-0.7		1.7	13.1	1.5	1000	0.32

Ice Thickness = 92 cm

Air Temperature = +0.3°C

TABLE 4.4
BASIC ICE PROPERTIES FOR CABOT ISLAND 9.5

DEPTH (CM)	T (°C)	DEPTH OF CORE (CM)	S (0/00)	σ_c (MPa)	σ_f (MPa)	E (MPa)	$\sqrt{\mu b}$ (0/00)
10	+0.8	0 - 17	1.2				N/A
20	10.3	17 - 37	1.5				N/A
30	-1.5	37 - 57	2.0	12.2	1.4	750	0.38
40	-1.3						0.28
50	-1.5	57 - 76	1.2				0.20
60	-1.3			13.0	1.4	500	0.22
70	-1.0	76 - 92	0.7				0.25
80	-0.8						0.22
90	-0.5						0.27
MEAN	-0.8		1.3	12.6	1.4	625	0.26

Ice Thickness = 92 cm

Air Temperature = +1.8°C

TABLE 4.5
BASIC ICE PROPERTIES FOR ST. JOHN ISLAND 1.0

DEPTH (CM)	T (°C)	DEPTH OF CORE (CM)	S (0/00)	σ_c (MPa)	σ_f (MPa)	E (MPa)	$\sqrt{\mu b}$ (0/00)
10	0.0	0 - 28	2.1				N/A
20	-1.0	28 - 51	3.4				.33
30	-1.4				1.1	500	.36
40	-1.6						.33
50	-1.8	51 - 75	2.4				.29
60	-1.7			10.4	1.2	750	.27
70	-1.3	75 - 93	1.7				.31
80	-1.1						.28
90	-1.0			9.6	1.1	500	.30
MEAN	-1.2		2.4	9.9	1.1	583	0.31

Ice Thickness = 93 cm

Air Temperature = +0.8°C

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Because the sample population was small as well as being restricted in location there were no regression analyses performed on the data collected.

Due to the mildness of the weather during the study period the ice was seen to be decaying in the upper layers. The ranges of the strength and elastic modulus values were relatively small.

Salinities measured at St. John Island 1.0 were higher than those measured on the Cabot Island line.

The major restrictions to shipping during the ice cover season would be large pressure ridges and areas of intense rafting. One of the criteria for the design of structures in ice infested waters is the solid ice thickness. An in-depth study of the strengths and void ratios in pressure ridges and heavily rafted areas is recommended as it indicates the ratio between total ice thickness and the thickness of solid ice.

Sufficient data should be compiled to allow for intelligent forecasts and estimations in planning activities in Lake Melville.



APPENDIX I



FENCO BOREHOLE JACK ICE STRENGTH

PROJECT: LAKE MELVILLE

SITE: CABOT ISLAND

BOREHOLE NUMBER: CORE #1

BOREHOLE LOCATION: CABOT ISLAND 7-5

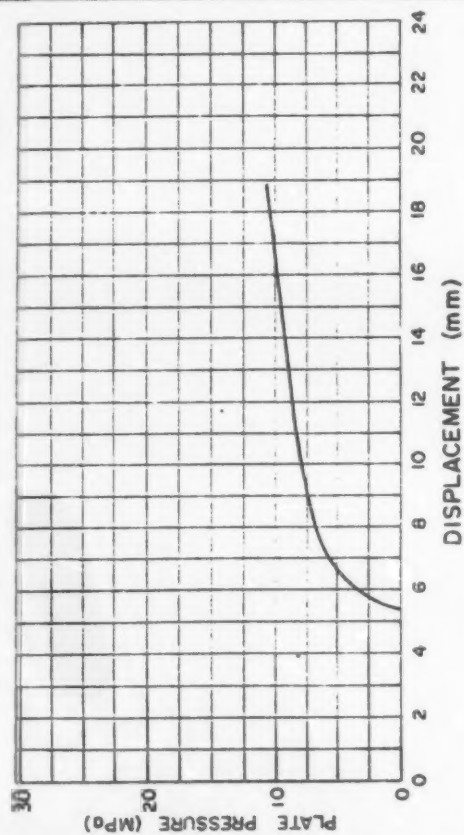
ICE THICKNESS: 89 cm

DATE: 26/O1/79

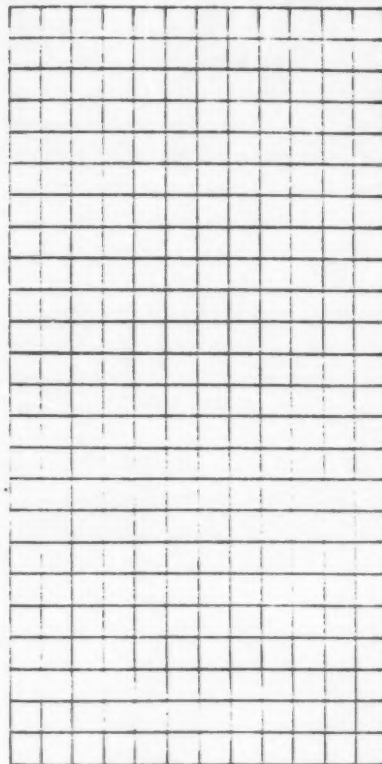
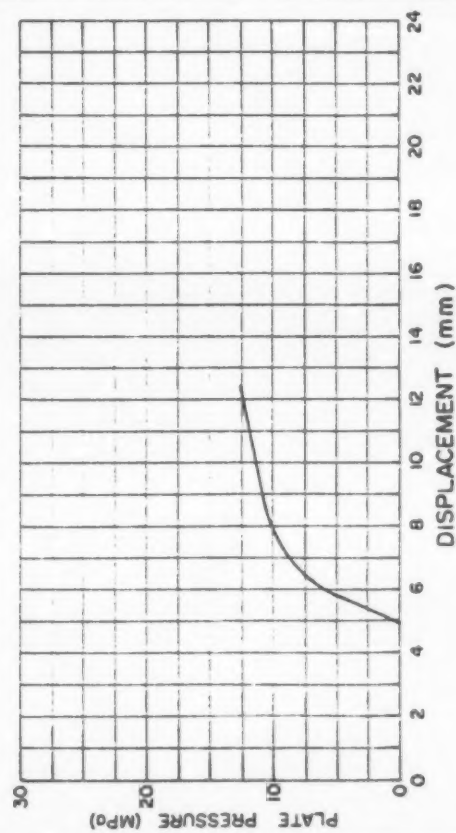
TECH: K.G.A.

- 93

DEPTH = 30 cm



DEPTH = 60 cm



FENCO BOREHOLE JACK ICE STRENGTH

PROJECT: LAKE MELVILLE

SITE: CABOT ISLAND

BOREHOLE NUMBER: HOLE #2, AT CORE #1

BOREHOLE LOCATION: CABOT ISLAND 7-5

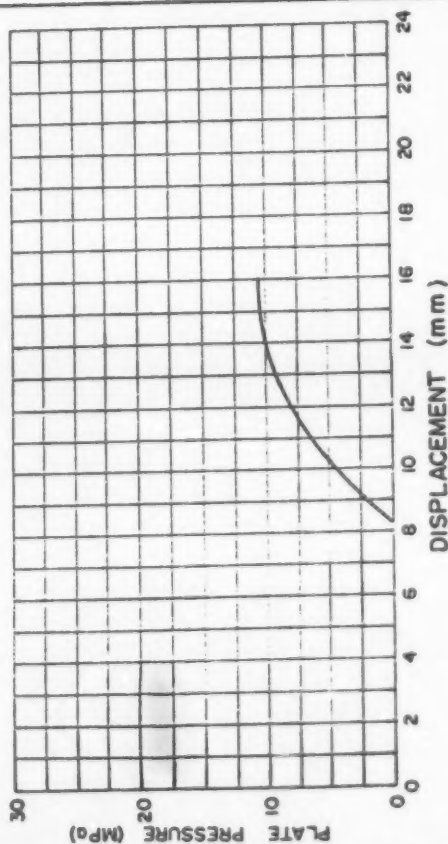
ICE THICKNESS: 85 cm

DATE: 26/01/79

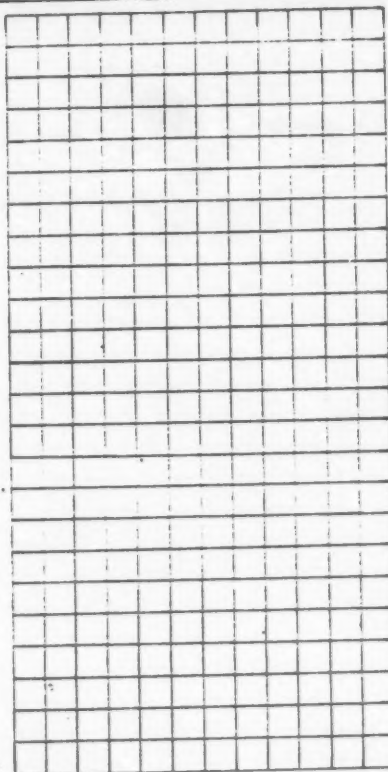
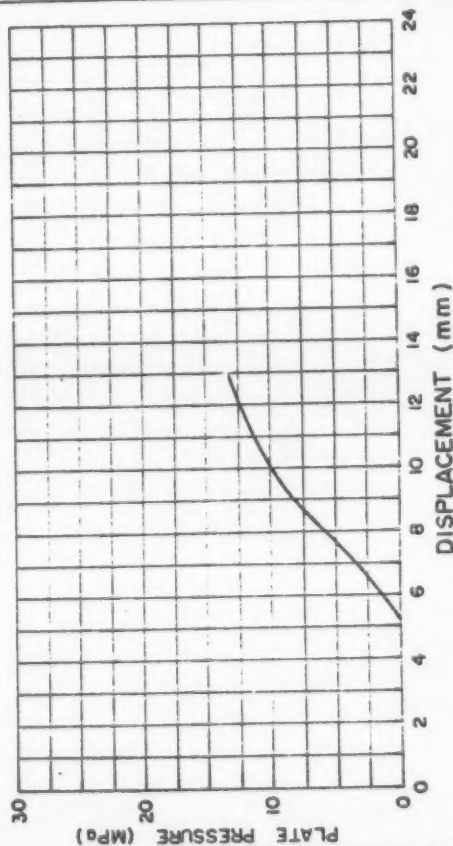
TECH: K.G.A.

- 94 -

DEPTH 30cm



DEPTH 60cm



FENCO BOREHOLE JACK ICE STRENGTH

PROJECT: LAKE MELVILLE

SITE: CABOT ISLAND

BOREHOLE NUMBER: CORE #2

BOREHOLE LOCATION: CABOT ISLAND 8-5

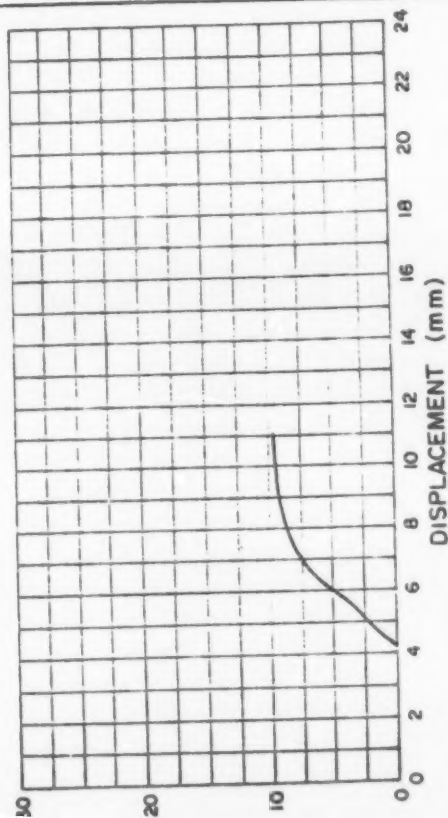
ICE THICKNESS: 92 cm

DATE: 27/01/79

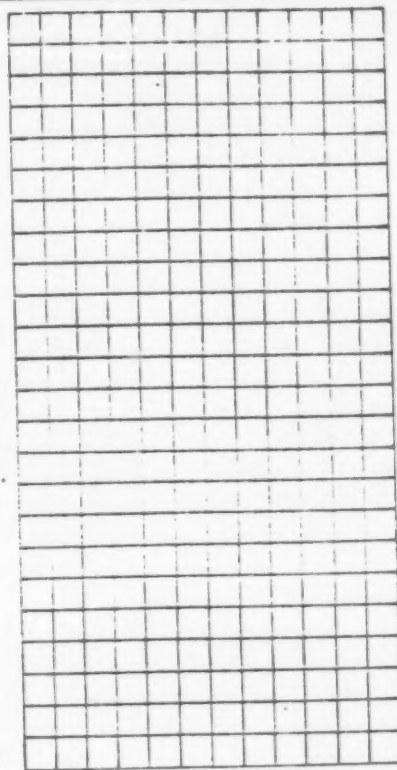
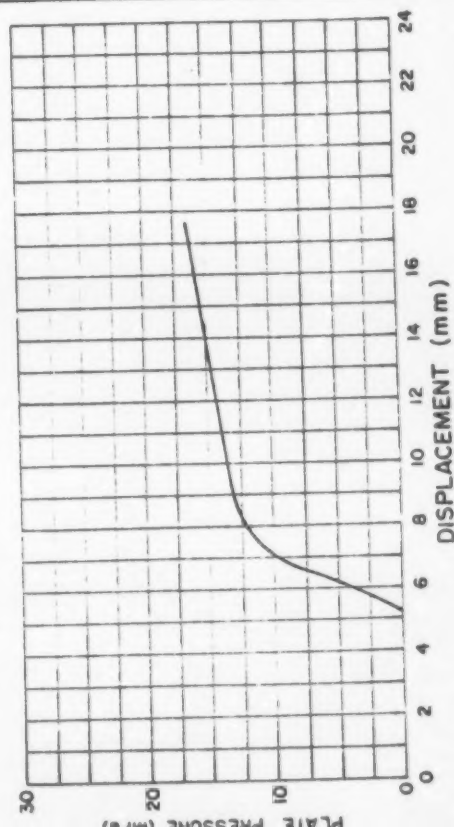
TECH: K.G.A.

- 95 -

DEPTH = 30cm



DEPTH = 60cm



FENCO BOREHOLE JACK ICE STRENGTH

PROJECT: LAKE MELVILLE

SITE: CABOT ISLAND

BOREHOLE NUMBER: CORE #3

BOREHOLE LOCATION: CABOT ISLAND 9-5

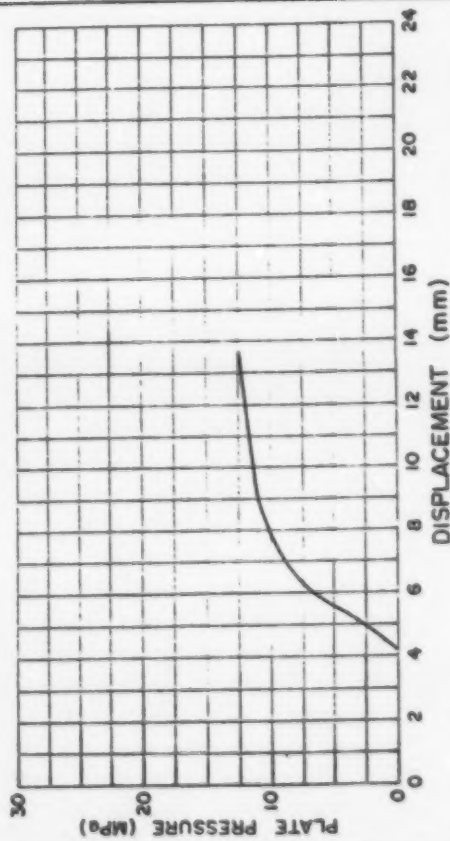
ICE THICKNESS: 92 cm

DATE: 27/01/79

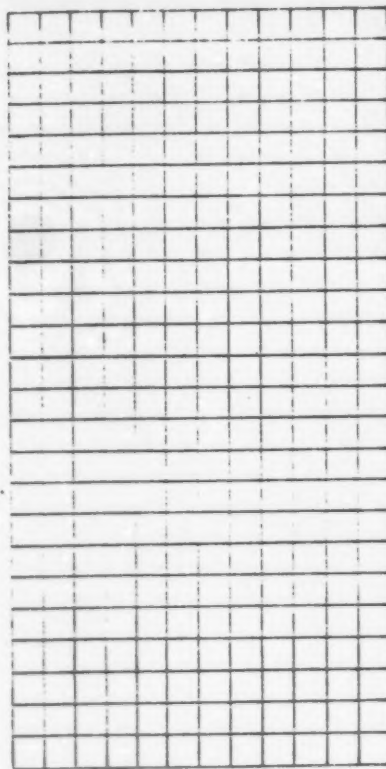
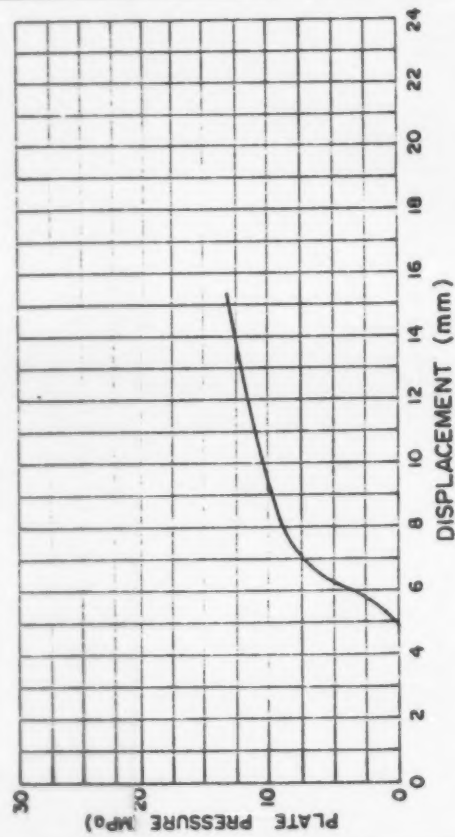
TECH: K.G.A.

- 96 -

DEPTH = 30 cm



DEPTH = 60 cm



FENCO BOREHOLE JACK ICE STRENGTH

PROJECT: LAKE MELVILLE

SITE: ST. JOHN ISLAND

BOREHOLE NUMBER: CORE #4

BOREHOLE LOCATION: ST. JOHN ISLAND 1-0

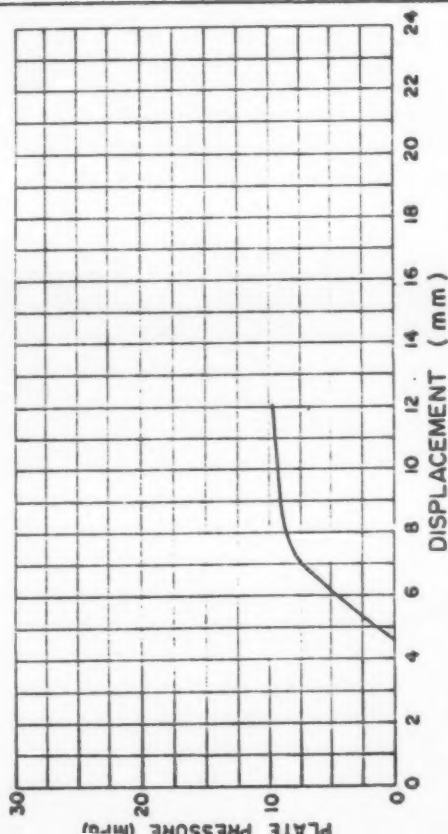
ICE THICKNESS: 93 cm

DATE: 29/01/79

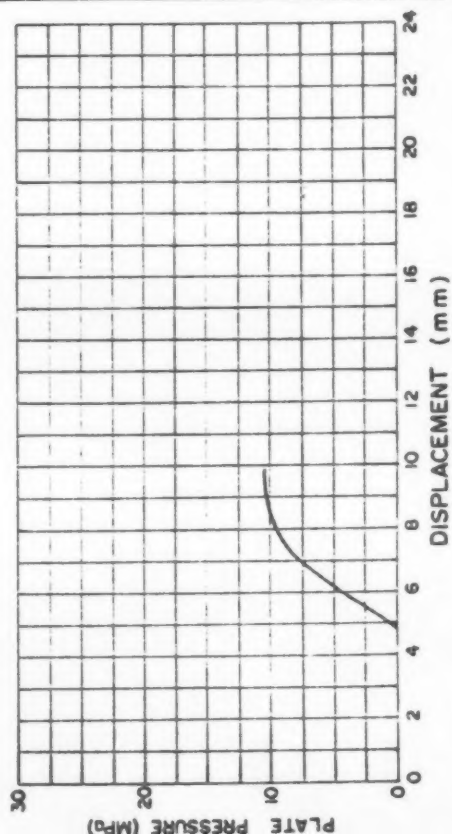
TECH: K.G.A.

- 97 -

DEPTH = 30 cm



DEPTH = 60 cm



DEPTH = 90 cm

